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B Curriculum Vitae

Personal Details

Name	Nicolas Christopher Liebau
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Education

Since 07/2002	To be obtained: Doktor-Ingenieur (Dr.-Ing.) in Electrical Engineering and Information Technology.
07/2006 – 09/2006	Visiting researcher at Lancaster University, UK with Dr. Andreas Mauthe.
08/1998 – 05/1999	Study abroad in the MBA-Program of the State University of New York at Buffalo, USA .
10/1994 – 06/2002	Studies of Joint Degree of Business Administration and Electrical Engineering, Technische Universität Darmstadt, Germany. Technical Specialisation: Data processing technology. Business Specialisation: Marketing. *Degree*: Diplom-Wirtschaftsingenieur (Dipl.-Wirtsch.-Ing.) in Electrical Engineering and Information Technology.
07/1980 – 06/1993	Elementary School, Secondary School, and High School. *Degree*: Allgemeine Hochschulreife.

Professional Experience

Since 10/2006	*Head of the P2P Networking* research group of the Multimedia Communications Lab (KOM), Department of Electrical Engineering and Information Technology, Technische Universität Darmstadt, Germany
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10/2002 – 06/2006	Head of computer administration group at the Multimedia Communications Lab (KOM), Department of Electrical Engineering and Information Technology, Technische Universität Darmstadt, Germany
07/2002 – 06/2005	Ph.D student with scholarship in the DFG Research Training Group „System Integration for Ubiquitous Calculations in the Information Technology“ at the Multimedia Communications Lab (KOM), Department of Electrical Engineering and Information Technology, Technische Universität Darmstadt, Germany
06/2001 – 08/2001	Internship at Accenture GmbH, Sulzbach/Taunus, Germany. Member of Operational Readiness Test Team on a project with the goal to build the functional foundation for the market presence of a new banking institute.
05/1999 – 08/1999	Internship at HR Foundations, Inc., Buffalo, NY, USA. Team member for designing and conducting Compensation & Salary Surveys.
07/1993 – 06/1994	Military service, Bundeswehr, Germany.

Supervision of Diploma-, Master-, Bachelor-, and Student-Theses

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C Supplementary Details to Chapter 2

C.1 Definitions in Context

Autonomous Distributed Systems

Autonomous Distributed systems are distributed systems (CDK02) where the participating entities are highly autonomous. Autonomous distributed systems include, e.g, p2p systems. Another example is a system of servers, where the servers are controlled by different parties and mutual trust does not exist.

Security

Security of information systems is a well defined term (see, e.g., (Eck04, Buc03, Sch96)). Eckert (Eck04) distinguishes functional security, information security, data protection, and privacy, where functional security is the basis of the other security terms. Typically, in information systems the term security refers to information security.

Functional security is the attribute of a system that the realised as-is functionality of the system components is consistent with the specified to-be functionality.

Information security (security) is the attribute of a functional secure system to take only those states which do not lead to any unauthorised modification of information or access to information.

Data protection is the attribute of a functional secure system to take only those states which do not lead to any unauthorised access to system resources and especially to data. Therefore, data protection also includes measures against loss of data like data backup.

Privacy is the ability of a physical person to control the propagation of data pertaining to that user.

For information security and data protection, there are six protection objectives defined. These are authentication, integrity, confidentiality, improper flow of information, availability, non-repudiation, anonymity, and pseudonymity.

Trustworthiness

In (Sta02) trustworthiness is described as "... an information system's accountability and its ability to produce reliable and authentic information and records. ... [Trustworthiness] denotes integrity, ability, faith, and confidence. We use trustworthiness to describe information system accountability." Accordingly, trustworthiness expresses the trust a user has in an information system. This includes security. In this definition accountability is an important term. Thus, it is not well suited for defining a trustworthy accounting system.

In (BHS02) Belanger states the three main elements of trust: *ability*, *benevolence*, and *integrity*. These elements correspond to characteristics of a merchant. Transferred to information systems, *ability* means the ability of an information system to fulfil the functionality it was designed for. Ability implies that the information system was designed with expertise in the relevant functional areas. *Integrity* refers to information security as defined above. *Benevolence* is defined as the extent to which the users believe that the application provider wants to do good things rather than just profit.

In information systems the term security refers typically to information security. However, for a trustworthy system this is incomplete, because aspects of functional security are missing. Therefore, in information systems the term *trusted entities* is used. It comprises also that the as-is functionality of the system components is consistent with system specifications. Belanger further adds benevolence as an element of a trusted information system.

This is an important addition for p2p systems, since the good intentions of all participating peers cannot be assumed. Thus, the challenge for p2p systems is to design a system that offers benevolence, although its components (peers) might not act honestly. Hence, potential cheating and collusion of peers must be considered in the design. In consequence, to design trusted p2p systems the application of state-of-the-art security mechanism will probably not be sufficient.

In sum, a trusted p2p system is designed with good intentions, the as-is functionality of the system is consistent with its specifications, and is secure without relying on (a) trusted entity(ies).

C.1.1 Definitions Related to Token-Based Accounting

Accounting

Accounting throughout this dissertation is defined as *the process of tracing* ***relevant*** *IS activities to a responsible source. Relevance is defined by the application applying accounting* (see Chapter 2, Section 2.1.2).

Account Holder

An account holder is a peer storing one or more aggregation accounts. See *Aggregation Account* as well as *Account Holder Set*.

Account Holder Set (AHS)

The account holder set (AHS) is a set of peers storing a specific aggregation account. A peer can be member of several account holder sets. Due to churn in the p2p system the membership in account holder sets is dynamic and changes over time as well as the exact location of an account holder set in the p2p system. Account holder sets are maintained using a set of maintenance mechanisms. The account holder set size (AHSS) is given the variable k throughout the dissertation. For details see Chapter 4, Section 4.2.

Aggregation Account

Each peer that is using the token-based accounting scheme requires an aggregation account. In the aggregation account the tokens issued to the peer are administered, that is the actual status of each token is stated. Aggregation accounts are located at remote peers, the so called account holder set. For details see Chapter 3, Section 3.6 as well as Chapter 4, Section4.2.

Aggregation Function

See *Token Aggregation*.

Quorum

The quorum of trusted peers is a randomly selected group of trusted peers that signs new tokens with their share of the token-based accounting scheme's private key during the token aggregation process in order to issue tokens. Using threshold cryptography an unanimous decision making of the quorum is implemented. The quorum size is given the variable t throughout the dissertation. Further details are described in Chapter 3, Section 3.2.

Token

Tokens are data objects that serve as a combination of transaction receipts and permission objects within the token-based accounting scheme. Tokens are issued to peers using the token aggregation process. During transactions tokens are spent in return for receiving an accounted service or accounted resources. For details see Chapter 3, Section 3.2.

Token Aggregation

For providing accounted services and accounted resources peers receive tokens belonging to other peers, so-called foreign tokens. Using the token aggregation process peers swap these foreign tokens against new own tokens they can use in order to receive accounted services and resources. The token aggregation process computes the number of new tokens a peer should receive using the aggregation function. New tokens are signed by a quorum of trusted peers with the token-based accounting scheme's private key using threshold cryptography. For details see Chapter3, Section 3.5.

Trusted Peer

A trusted peer is in possession of one share of the token-based accounting scheme's private key. This key is shared among all trusted peers and signatures are created by a quorum of trusted peers using threshold cryptography. Trusted peers are selected based on their reputation value. Details about trusted peers are described in Chapter 4, Section 4.3.

C.1.2 Definitions Related to Threshold Cryptography

Secret (s)

A secret denotes a secret key. A secret key is an encryption key that is kept concealed. Its discovery voids the security of the encryption session. A secret key generally refers to the key in a secret key cryptography system, in which both sides use the same key. It may also refer to the private key in a public key cryptography system, because the private key must also kept secret. (From (THe06), Secret Key).

Share (s_i)

The share s_i is a mathematical derived value of the secret s. A predefined number of the shares are needed to reconstruct the secret. These shares have to be stored secretly. An important property of these

shares is that no information about the secret is revealed, if less than the predefined number of shares is known by an attacker. (cf. (HJKY95).)

Dealer (D)

A dealer (of a (k, n)-threshold scheme) owning a secret s wishes to distribute knowledge of s (shares) among a group of shareholders such that two conditions hold:

Correctness: Any subset of k shareholders can together recover s

Security: Any subset of less than k shareholders cannot recover s The dealer is only used to share the secret s and destroys its information if the shares are distributed correctly. (cf. (PSW04).)

Shareholder (P_i)

A shareholder P_i receive a unique share from the dealer D and stores it securely. To reconstruct the secret s the shareholders are consulted, which deliver the shares for reconstruction (cf. (WWW02)).

(k, n)-Threshold Scheme

A (k, n)-threshold scheme is a way of distributing partial information called shares to n participants in order to allow any k of them to make an action (e.g., to find a secret s or to open a vault in a bank), but also to ensure that the action cannot be made by any subset of fewer than k participants. (From (TMOO05).)

Secret Sharing

A trusted dealer TP gives each player P_i a secret share ss_i of the secret s in such a way, that any group of t or more players can together reconstruct the secret, but no group fewer then t players can do this. Here, t is denoted the threshold and n is the total number of players.

Verifiable Secret Sharing

A secret sharing scheme is verifiable secret sharing scheme (VSS) if additional information is made available to the players that enables the players to verify that their shares are consistent. I.e. even when the dealer is malicious there is a well defined secret that the players can reconstruct.

Proactive Secret Sharing

A *Proactive Secret Sharing* scheme enhances threshold schemes by periodic refreshment of the shared function in such a way that the secret kept unchanged. Breaking of the system requires the attacker to break into several shareholders in a short period of time. (HJJK97)

Initialisation Phase

In *initialisation phase* the secret s is encoded into n shares using a (k, n)-threshold scheme. These shares are then distributed securely to the shareholders. At the end of this phase each good shareholder has a

valid and verified share. With this share the shareholder is able to participate the reconstruction phase. (cf. (HJKY95, NNPV02b).)

Reconstruction Phase

In *reconstruction phase* a defined coalition of shareholders cooperate to reconstruct the secret or to generate a signature. Therefore, the corresponding reconstruction protocol is performed. (NNPV02a)

Update Phase

Within the *update phase* the shares of the shareholders are updated without changing the secret s. This phase is performed periodically. At the end of the update phase the updated shares correspond to the secret s. An attacker that knows no more than k shares from different update periods learns nothing about the secret. (HJKY95)

Recovery Phase

The *recovery phase* is used to recover malicious shareholders. First all corrupted shareholders are identified and then recovered. For recovery a coalition of good shareholders has to cooperate to generate a new share. (HJKY95)

Passive Adversary

A passive adversary obtains the complete information held by the attacked shareholder, but the attacked shareholder executes the protocol correctly. (NN04)

Active Adversary

An active adversary takes full control of the attacked shareholder and is able to change the behaviour of the shareholder. (NN04)

Mobile Adversary

A mobile (active) adversary can corrupt a shareholder during any time period. Corrupting a shareholder means any combination of learning the secret information, modifying its data, changing its intended behaviour, disconnection it from communication channel, etc. The adversary is connected to the broadcast channel, which means that he can hear all broadcasted messages or broadcast his own (DoS-attack possible). He is not able to modify messages sent between shareholders that he does not control, nor can he pretend non-corrupted shareholders from receiving a broadcasted message. (Additionally, the adversary is computationally bounded, so that it cannot break the underlying cryptographic primitives (e.g., solving the discrete logarithm problem)) (HJJK97).

C.1.3 Definitions of Related Forms of Attacks in Context

This section summarises the forms of attack that are especially relevant the context of the thesis.

Cheating

Cheating is an attack where a peer improves its own situation in the p2p system, e.g., by spreading false information or by using an alternative protocol.

Within the context of the token-based accounting scheme cheating is every form behaviour where a peer aims at increasing it amount of tokens in a wrongful way.

Collusion Attack

In an collusion attack a number of peers collaborate with the goal to defraud the system.

An example is a p2p file sharing application where upload is higher valued than download. Here, two peers could collude and claim they shared many files in order to manipulate the measured contribution of these two peers to the system.

Hitchhiking

Hitchhiking is an attack known from reputation systems. Here, a peer is making use of another peer's high reputation with or without this peer's knowledge.

Within the context of the token-based accounting scheme, a peer that makes use of another peer's account status in order to receive accounted resources or services would hitchhike.

Sybil Attack

The Sybil attack was first presented in (Dou02). It is an attack in p2p systems, where a single faulty peer presents multiple identities and by this means attempts to control a substantial fraction of the system, in order to defraud the system.

The Sybil attack is to be considered where trusted data is replicated in a p2p systems. With a successful Sybil attack a peer could control the majority of replicas of the data.

Whitewashing Attack

Whitewashing is an attack known from reputation and incentive systems. Typically, in such systems new peers receive a specific initial rating. A peer that gained over time a rating that is below that initial rating, can "white wash" itself by discarding its identity and taking a new one.

Double Spending

In digital currency systems and similar systems double spending is attack, when a peer spends a single currency unit several times, in order to avoid payment. In the token-based accounting scheme double spending refers to using a token more than once in order to pay for accounted resources or services.

Forgery

Forgery is the process where a peer forges a digital document issued by some entity. Forgery often includes forging a digital signature. In the token-based accounting scheme, forgery refers to forging a signature of the scheme's private key.

C.1.4 Definitions Related to Commercial Transaction Processes

C.1.4.1 Resources

In (Car08) resources are defined as CPU, Memory, I/O, Peripheral, Network. Within p2p systems often bandwidth, storage capacity, and processing power are named as the relevant resources (Shi01, SW05a).

Resources are used in order to provide services in p2p systems. As in p2p systems services are provided between peers, the resource bandwidth is always required and therefore it is the most important resource.

C.1.4.2 Services And Transactions

In accordance with *(Mer08)* a transaction is *"something transacted; especially: an exchange or transfer of goods, services or funds"*. A good can be for example a specific digital content like an mp3-song. A service can be can vary from resource usage (e.g., calculations performed on a remote peer like in SETI@Home (Uni08), the storage of a file for a specific period of time like in OceanStore (UC 08)) to complex services (e.g., a radiologist does a diagnosis of an x-ray).

In p2p systems all transactions involve a data transmission service; either file transfer, a streaming service, or simply a message transfer. Therefore, for simplicity, in this dissertation all transaction objects (goods, services, funds from the above definition) accounted for are from now on summarised under the term *services*.

C.1.4.3 Price And Tariff

A price is "... an amount of money associated with a unit of service; this is used to compute the charge. The tariff refers to the general structure of prices and charges. A example of a tariff is $a + pT$, where a is a price for setting up, p is a price per second for using the service, and T is the duration of the connection in seconds. A tariff is that part of the contract between two parties that specifies the way the charge will be computed for the service." (CW03)

C.1.4.4 Charging

A *charge* is the amount that is billed for a service (CW03). Accordingly, charging is the process of computing the charge according the tariff agreed by the transaction partners for the service. Charging requires as input accounting information about the service.

C.1.4.5 Billing

In this dissertation billing is the process of creating a document, the bill, stating the amount a service consumer has to pay to the service provider. Billing requires as input from charging the relevant information that must be included in the bill: customer, provider, transaction object, charge, date, and potentially further information.

C.1.4.6 Payment

Payment is "the partial or complete discharge of an obligation by its settlement in the form of the transfer of funds, assets, or services equal to the monetary value of part or all of the debtor's obligation." (Web08)

Payment as functionality can be provided by an application or service external to the IT-system used to deliver the primary service of a transaction from provider to customer.

C.2 Details on Security Mechanisms for Distributed Systems

C.2.1 Secret Sharing

This section gives further details to different secret sharing techniques.

C.2.1.1 XOR Secret Sharing

A secret s has to be shared between n shareholders using XOR Operation (see (DW04)). The different shares are constructed and distributed in the initialisation phase and reconstructed in the reconstruction phase.

Initialisation Phase

To distribute the secret a trusted dealer D chooses $n-1$ random values $(s_1, s_2, \ldots, s_{n-1})$ that are used as shares and the last share is constructed using Equation C.1. Then, these shares are sent secretly to the shareholders $(P_1, \ldots, P_n)$ that store the share.

$$s_n = s \oplus s_1 \oplus s_2 \oplus \ldots \oplus s_{n-1} \tag{C.1}$$

Reconstruction Phase

To reconstruct the secret s all shares of the shareholders have to be combined using the XOR-Operation. Thus, all shares are sent to one shareholder that performs Equation C.2 for reconstruction.

$$s = s_1 \oplus s_2 \oplus \ldots \oplus s_n \tag{C.2}$$

C.2.1.2 Additive Secret Sharing

Similar to XOR secret sharing, additive secret sharing can be used. Instead of using the XOR operation, an addition is used. Additive secret sharing is, e.g., used and presented in (Rab98) and (JS05).

Initialisation Phase

Equivalent to the XOR secret sharing scheme, a trusted dealer D generates $n-1$ random numbers $(s_1, s_2, \ldots, s_{n-1})$. The missing last share is computed using Equation C.3. Then, these shares $s_1, s_2, \ldots, s_n$ are distributed secretly to the corresponding shareholders $(P_1, P_2, \ldots, P_n)$.

$$s_n = s - \sum_{i=1}^{n-1} s_i \tag{C.3}$$

Reconstruction Phase

The common approach to reconstruct the secret s is to send all shares to a shareholder that reconstructs the secret using Equation C.4.

$$s = \sum_{i=1}^{n} s_i \tag{C.4}$$

A disadvantage of the approach presented above, is that the secret is revealed. This reduces the security of the secret sharing scheme, since an attacker has the possibility to obtain the secret. However, if the secret s is used for cryptographic tasks using RSA, s does not need to be revealed.

The functions to decrypt, encrypt and sign messages using RSA are presented below. Equation C.5 is used to encrypt a message m and Equation C.6 is used to decrypt the encrypted message or to sign a message. In this context, d and e are the private and the public key. Thus it is very probably that the secret s will be equal to the private key d.

$$c = m^e \bmod N \tag{C.5}$$

$$c^d \bmod N = m^{ed} \bmod N = m \tag{C.6}$$

For information on RSA: to construct d, e one has to choose two primes (p, q) and compute the product $N = pq$ of them. Then the public key e is chosen using Equation C.7 and the private key d using Equation C.8. For more information about RSA see e.g. (Buc03).

$$1 < e < \varphi(N) = (p-1)(q-1) \wedge gcd(e, (p-1)(q-1)) = 1 \tag{C.7}$$

$$1 < d < \varphi(N) = (p-1)(q-1) \wedge de = 1 \bmod (p-1)(q-1) \tag{C.8}$$

If the private key d is shared between n shareholders and a message m has to be signed, the shareholders have to perform the following tasks:

Each shareholder P_i ($i \in \{1, \ldots, n\}$) computes a partial signature $sig_{s_i}(m)$ (see Equation C.9) and sends this partial signature to the requester of the signature. Then the requester has to multiply each partial signature to get the final signature $sig_s(m)$ (Equation C.10).

$$sig_{s_i}(m) = m^{s_i} \bmod N \tag{C.9}$$

$$sig_s(m) = \prod_{i=1}^{n} sig_{s_i}(m) \bmod N = \prod_{i=1}^{n} m^{s_i} \bmod N = m^{\sum_{i=1}^{n} s_i} \bmod N = m^s \bmod N \tag{C.10}$$

This is possible, because of the mathematical rules for exponentiation (Equation C.11 and C.12).

$$a^b a^c = a^{b+c} \tag{C.11}$$

$$(a^b)^c = a^{bc} \tag{C.12}$$

It is important to notice that it is mandatory to use integers as values for the shares $(s_1, \ldots s_n)$. If non natural numbers are used it is not be possible to compute the partial signature (because one has to compute the root modulo N). Additionally, it will be good if all shares are positive integer. Using negative integers, one has to compute the inverse modulo of the message $m \bmod N$. This is possible as long as m is relative prime to N. Note that, if one finds a message m that is not relative prime to N, $N = pq$ is factorised and the RSA scheme is broken (or can be broken very easily).

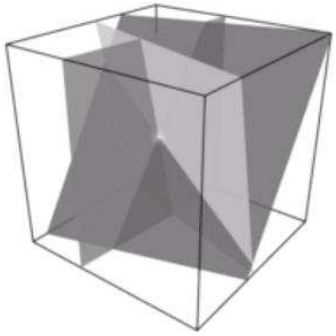


Figure C.1: Blakely's secret sharing (from (RSA04))

C.2.1.3 Blakely's Secret Sharing

Blakely developed another historical secret sharing scheme presented in (Bla79). It is not often mentioned in literature and thus, only the principle and not the details are presented here.

Blakely uses the intersection of hyperplanes to represent the secret. Therefore each share is a hyperplane in a m-dimensional space. To reconstruct the secret, at least m shares are needed and the intersection of these planes is used. Figure C.1 shows the secret sharing scheme within a 3-dimensional space. The secret can either be expressed as a coordinate of the axes or as the absolute value of the vector from the point of origin to the point of intersection (see (RSA04)).

One disadvantage of Blakely's scheme is, that the shareholder knows, that the secret is on its hyperplane. This can help to find the secret faster in comparison to Shamir's scheme, where the shareholder has no information about the secret. Additionally, one has to mention, that the secret has to be completely reconstructed, e.g., to decrypt, sign and encrypt messages. Shamir's scheme offers, e.g., the possibility to create partial signatures that can be combined to create the final signature (see Section 2.4.7.1).

C.2.2 Verifiable Secret Sharing

This section presents some well-known secret sharing schemes and evaluates them, including Pedersen's Verifiable Secret Sharing, which is presented in Chapter 2.4.5.1.

C.2.2.1 Feldman's Verifiable Secret Sharing Scheme

Feldman developed a popular verifiable secret sharing scheme. It is based on Shamir's scheme (polynomial interpolation) and presented in (Fel87). It increases the security by allowing the shareholders to check the correctness of the shares provided by the dealer. Therefore, the dealer broadcasts some verification values. These values do not reveal any information about the secret, because they are based on hardness of computing discrete logarithms. The detailed steps for verification in initialisation and reconstruction phase are presented below.

Initialisation Phase

The initial steps of Feldman's scheme are similar to the Shamir's scheme. The dealer chooses two prime numbers p and q, such that $p = mq + 1$ (m is a small integer) and creates a random polynomial function $f(x) \bmod q$ of degree $k - 1$ (see Equation 2.1). Then the dealer transmits the shares $(s_1 \dots s_n)$ constructed with Equation 2.2 to the shareholders.

Additionally the dealer computes the public verification values ($y_i = g^{\alpha_i}$) of the polynomial function. Whereas α_i ($i = \{0, \dots, k-1\}$) are the coefficients of the polynomial from Equation 2.1 and $g \in Z_p$

of order q. These public values $(g^s, g^{\alpha_1}, \ldots, g^{\alpha_{k-1}})$ are then broadcasted to all shareholders, which can now check the correctness of the received shares by using Equation C.13.

$$\begin{aligned} g^{s_i} &\equiv (g^s)(g^{\alpha_1})^i(g^{\alpha_2})^{i^2}\ldots(g^{\alpha_{k-1}})^{i^{k-1}} \bmod p \\ &\equiv g^{s+\alpha_1 i+\alpha_2 i^2 \ldots \alpha_{k-1} i^{k-1}} \bmod p \end{aligned} \tag{C.13}$$

Whereas i is the value of the variable used to compute the share s_i for shareholder P_i ($s_i = f(i)$).

If Equation C.13 holds, each shareholder broadcasts a message that it accepts the received share (and trusts the dealer). If all shareholders accept its share, the shares are distributed successful and the initialisation phase ends. But, if a shareholder identifies an incorrect share, it publishes an accusation against the dealer. Then the other shareholders have to decide whether to trust the shareholder or the dealer. Therefore, the dealer publishes additional information, that each shareholder can verify the accused share.

Reconstruction Phase

The verification methods can also be applied in reconstruction phase. Therefore, each shareholder has to store the public verification values broadcasted by the dealer in initialisation phase. Now he can check the correctness of the shares, received to reconstruct the secret s. If one of the received shares is incorrect, an accusation is broadcasted against the corresponding shareholder and another share is requested from a different shareholder. The disadvantage of the verification methods is that it cannot be applied for partial signatures (e.g. $m^{s_i} \bmod N$).

C.2.2.2 Verifiable Secret Sharing with A Symmetric Polynomial

Beside Shamir's secret sharing scheme with one variable, secret sharing schemes with two variables exist. In this section a secret sharing scheme based on a symmetric polynomial is presented. It is unconditional secure, this means that each shareholder checks the correctness of its shares with each other shareholder in the secret sharing scheme. It is presented among others in (SW99).

Initialisation Phase

For the verifiable secret sharing scheme with a random symmetric polynomial function, the dealer D constructs a function following Equation C.14 with $a_{00} = s$ and $a_{ij} = a_{ji}$.

$$f(x,y) = \sum_{i=0}^{k-1}\sum_{j=0}^{k-1} a_{ij}x^i y^j \tag{C.14}$$

Each shareholder P_i ($i = \{1, \ldots, n\}$) receives its share (a function) $s_i(x) = f(x, \omega^i)$ from the dealer, whereas ω is an element of the finite field generated with the prime number q. And ω is known by all other shareholders participating the verifiable secret sharing scheme. To verify the received share, each P_m sends $s_i(\omega^j) = f(\omega^j, \omega^i)$ to shareholder P_j $j \in \{1..n \mid j \neq i\}$. Then shareholder P_j performs the verification using Equation C.15.

$$s_i(\omega^j) = s_j(\omega^i) \Leftrightarrow f(\omega^j, \omega^i) = f(\omega^i, \omega^j) \tag{C.15}$$

Equation C.15 holds, since $f(x,y)$ is a symmetric polynomial function. If the check fails, the corresponding shareholder P_j broadcasts (i,j) the index of the shareholders for that the equation does not hold. At the end of the initialisation phase each shareholder has the same set of valid shareholders. If the number of valid shareholders is greater than a certain threshold (e.g. n-k) the initialisation phase

was successful. Otherwise the dealer is malicious, since per definition only $k-1$ shareholder may be malicious.

Another approach to verify the shares distributed by the dealer is presented in (NN04). If shareholder P_j decides that Equation C.15 does not hold, an accusation is broadcasted. If more than $k-1$ accusations were broadcasted, the dealer is malicious. Otherwise the share $s_i(x)$ of shareholder P_i has to be revealed and all participating shareholders can check whether the dealer D, shareholder P_i or shareholder P_j is malicious.

Reconstruction Phase

To reconstruct the secret Lagrange interpolation is used (Equation 2.3). Therefore, at least k shareholder P_i, $i \in \{1,\ldots,n\}$ have to send their share $s_i(x)$, e.g., to a shareholder that checks the correctness of the shares and reconstructs the secret s using Equation 2.3 and $(i, s_i(0))$ as input values.

The shareholder (e.g. P_j) that reconstructs the secret, checks if $s_j(\omega^i) = s_i(\omega^j)$ for the shares $s_i(x)$ received from shareholder P_i, $i \in \{1,...n\}$. If the equation holds, the secret can be computed. Otherwise, the wrong share is sorted out and the shareholder is accused. Since $k-1$ shareholder may be malicious it will be mandatory to have at least $2k-1$ shares for verification. So it will be guaranteed that at least k correct shares are available.

Additionally, it is possible to generate partial signatures that can be used for cryptographic tasks (using RSA). Therefore, each shareholder creates the partial signature $sig_{s_i}(m)$ using Equation C.16. The verification of these messages is not possible.

$$sig_{s_i}(m) = m^{s_i(0)} \bmod n \tag{C.16}$$

C.2.2.3 Verifiable Secret Sharing with An Asymmetric Polynomial

Instead of a symmetric polynomial it is possible to use an asymmetric one. This involves a bit more overhead, like presented in the following section. The scheme is presented among others in (NN04).

Initialisation Phase

A dealer D creates an asymmetric polynomial $f(x,y)$ using Equation C.17 with $a_{ij} \neq a_{ji}$ and $a_{00} = s$. Then D computes the shares $s_i(x) = f(x,\omega^i)$ and $t_i(y) = f(\omega^i, y)$ for each shareholder P_i ($i \in \{1,\ldots,n\}$). Whereas, similar to Section C.2.2.2, ω is an element of the finite field generated with a prime number q.

$$f(x,y) = \sum_{i=0}^{k-1}\sum_{j=0}^{k-1} a_{ij}x^i y^j \tag{C.17}$$

To verify the received shares, shareholder P_i ($i \in \{1,\ldots,n\}$) first checks if $s_i(\omega^i) = t_i(\omega^i)$. If this equation does not hold, P_i broadcasts an accusation against the dealer D. Otherwise P_i computes for each shareholder P_j ($\{j \in \{1,\ldots,n\} | j \neq i\}$) the verification values $s_i(\omega^j)$ and $t_i(\omega^j)$ and distributes them secretly. Upon receive of these verification values P_j compares its shares with the all received values (s_i, t_i) using Equation C.18.

$$s_i(\omega^j) = t_j(\omega^i) \wedge t_i(\omega^j) = s_j(\omega^i) \tag{C.18}$$

If this equation does not hold, shareholder P_j broadcasts (i,j) and the accusation can be resolved using the methods presented in Section C.2.2.2.

Reconstruction Phase

The reconstruction phase of the secret is equal to the reconstruction of a secret sharing scheme with symmetric polynomial. At least k shareholder P_i, $i \in \{1, \ldots, n\}$ send their shares $s_i(x)$, $t_i(x)$ to a shareholder (e.g. P_j) that reconstructs the secret s using Equation 2.3 (either with $(i, s_i(0))$ or $(i, t_i(0))$ as input values). Before reconstruction, the received shares can be verified, by checking $s_i(\omega^j) = t_j(\omega^i) \wedge t_i(\omega^j) = s_j(\omega^i)$. If the checks are correct the values can be used to reconstruct the secret. Otherwise an accusation is broadcasted and another share has to be used.

Again it is mandatory to use at least $2k-1$ shares for reconstruction, because at most k shares may be malicious. And it is also possible to generate partial signatures using $s_i(0)$ or $t_i(0)$.

C.2.2.4 Summary

Verifiable secret sharing is an important feature for applying a secret sharing scheme in autonomous distributed systems.

The schemes of Feldman et al. and Pedersen are based on the problem to solve the discrete logarithm. In difference to Feldman et al., Pedersen scheme reveals no Shannon information (see (Sha01) for further information). This means, if the value s is verified using Feldman, the corresponding verification value g^s is always the same. Pedersen randomises the verification value by choosing a random parameter t. So the verification value of s is different ($g^s h^{t_1} \neq g^s h^{t_2}$). This avoids that an attacker that knows a share s_i and the corresponding verification value does not know when the same share is reused by a fluke.

Stinson and Wei use polynomials with two variables and thus do not have to generate and broadcast extra verification values. That is the advantage of this approach. Each share enables the verification of all other shares in the scheme. However, if a high threshold is assumed (e.g. a $(20, 100)$-threshold scheme), this approach results in very large shares.

C.2.2.5 Frankel's RSA-based Threshold Cryptography Scheme

The scheme of (FGMY97a) can be applied for both, polynomial secret sharing (Section 2.4.4.1) as well as additive secret sharing (Section C.2.1.2). The principle is to avoid non-natural numbers of the Lagrange coefficients by extending the exponent. In the following the focus is on polynomial secret sharing. The additive extension is not presented in detail.

Initialisation Phase

The dealer D chooses two primes p, q and generates the public key e and private key d. The private key d is shared among the shareholders. In the following is $L = n!$, whereas n is number of shareholders. Additionally, it is assumed that the shareholders are indexed from $1, \ldots, n$. The dealer performs the following mathematical operations to generate a proper polynomial and to share the private key d.

- D computes the greatest common divisor $H = gcd(e, L^2)$
- Two natural numbers P and s' are computed such that $1 = eP + \frac{L^2}{H}s'$ (using extended Euclidean algorithm)
- k' is computed such that $d \equiv P + L^2 k' \bmod (p-1)(q-1)$ and $k' \equiv ds'H^{-1} \bmod (p-1)(q-1)$. Whereas H^{-1} is the inverse of H modulo $(p-1)(q-1)$.

Then the dealer chooses similar to Shamir (Section 2.4.4.1) a random polynomial $f(x) = \sum_{i=0}^{k-1} f_i x^i$ with $f(0) = L^2 k'$ and $f_i \in \{0, L, \ldots 2L^3 n^{2+\epsilon} t\}$ (ϵ is an optional security factor). Then the shares $s_i =$

$f(i)$ ($i = \{1, \ldots, n\}$) are computed and secretly distributed to the corresponding shareholder P_i. The parameter P is either distributed to each shareholder or published. Additionally to the shares, D chooses and distributes two generators g, g_1 for verification and publishes $g^{s_i L^2} \bmod n$ for all $i \in \{1, \ldots, n\}$.

Reconstruction Phase

For reconstruction Equation C.19 is used. A predefined group $\mathcal{A}$ of k shareholders compute the partial keys k_i (Equation 2.6). The private key d is reconstructed using Equation C.19.

$$d = P + \sum_{i \in \mathcal{A}} k_i \tag{C.19}$$

The advantage of this scheme is that each share is a multiple of $L = n!$. Therefore, the sum of Equation C.19 is done over integers. To generate a partial signature $sig(m) = m^d \bmod N$ each shareholder in $\mathcal{A}$ computes $sig_{s_i}(m) = m^{k_i} \bmod N$ and sends this partial signature to the signature requester. Then the requester combines the received signatures using Equation C.20.

$$m^d = m^P \prod_{i \in \mathcal{A}} m^{k_i} \tag{C.20}$$

The parameter P can either be added by a defined shareholder or send to the requester that can compute the signature by himself.

Additionally it is possible that more then k shareholders send a partial signed message m^{s_i} to the requester. Then the requester has to pick k partial signatures, generates m^{k_i} and performs Equation C.21. So, the shareholders have not to communicate to create a signature.

$$m^d = m^P \prod_{i \in \mathcal{A}} ((m^{s_i})^{\sum_{j \in \mathcal{A} \setminus i} \frac{-j}{i-j}}) \tag{C.21}$$

Summary

Although this scheme circumvents the problem of negative numbers or non-natural numbers in the exponent, it has a limitation that prohibits its application large distributed anonymous systems. In order to avoid non natural numbers in the Lagrange coefficients, one has to compute the factorial of the number of shareholders. This will be applicable for threshold groups with around up to 100 shareholders, but not for threshold groups with thousands of shareholders. Accordingly, this scheme can be applied in server-based environments like COCA (ZSvR02). However, it is not suited for large p2p systems.

D Supplementary Details to Chapter 4

D.1 Account Holder Set

D.1.1 Peer Assignment, Information Storage and Retrieval

D.1.1.1 Aggregation Account Creation

Checking for Account Existence

Algorithm 4.2 Check for Aggregation Account Existance

This algorithm describes the procedure how a peer P_1 can determine, if the aggregation account for a peer P_C exists.

1. Peer P_1 sends a check_aggregation_account_req($queryID$, AA_C^{ID}, hc, $peerID(P_1)$) to the peer responsible for AA_C^{ID}, P_C, with the hop counter hc set to -1.
2. Whenever a peer P receives a check_aggregation_account_req($queryID$, AA_C^{ID}, hc, $peerID(P_1)$) message,
    1. P checks if it hosts the aggregation account for AA_C^{ID}. If true, P creates an aggregation_account_status($queryID$, AA_C^{ID}) message and sends it to $peerID(P_1)$.
    2. Else, P creates a check_aggregation_account($queryID$, AA_C^{ID}, hc, $peerID(P_1)$) message and forwards it to its successor and to its predecessor on the DHT.
3. Whenever a peer P receives a check_aggregation_account($queryID$, AA_C^{ID}, hc, $peerID(P_1)$) message,
    1. P checks if it hosts the aggregation account for AA_C^{ID}. If true, P creates an aggregation_account_status($queryID$, AA_C^{ID}) message and sends it to $peerID(P_1)$.
    2. Else, P increases the hopcounter hc by one.
    3. If $hc < X_{max}$, P forwards the message to its successor $succ(P)$ to it predecessor $pred(P)$ on the DHT, $succ(P)$, depending on the direction P received the message from.
    4. Else P creates an aggregation_account_failure($queryID$, AA_C^{ID}) message and sends it to P_1.

Aggregation Account Creation

Algorithm 4.3 Aggregation Account Creation

This algorithm is used to create a new aggregation account for a peer P_{new}.

1. A new peer P_{new} contacts trusted peer TP_1 in order to request new tokens (token aggregation or start-up number of tokens).
2. TP_1 checks if aggregation account for P_{new} exists using Algorithm 4.2.

3. If aggregation account for P_{new} does not exist,
    1. TP_1 calculates the aggregation account ID $AA^{ID}_{new}$for P_{new}.
    2. TP_1 looks up the peer responsible for AA^{ID}_{new}, denoted P_C.
    3. TP_1determines x, the number of hops AA_{new} should be shifted on the DHT.
    4. TP_1 randomly picks r values y, where $1 + 2r + \sum_{i=1}^{r} y_r = x$.
    5. Set $P_k = P_C$.
    6. For $i = 1$ to r do:
        1. Set $P_i = P_k$.
        2. TP_1 looks up the P_i's successor on the DHT, P_j.
        3. TP_1sends request_peer message containing $(y_i - 1)$ to P_j.
        4. P_j forwards the request_peer message to its $(y_i - 1)$-th successor, P_m.
        5. P_m responds to TP_1 with its successor's peerID, P_k.
    7. P_k is the peer with $x-1$ hops distance to P_C. TP_1 sends an init_aggregation_account(AA^{ID}_{new}) message to P_k's successor on the DHT, P_{AH1}.
    8. P_{AH1} initiates the aggregation account AA_{new} using Algorithm 4.4. When done, P_{AH1} sends an aggregation_account_confirmed message to TP_1.
4. Upon receiving the aggregation_account_confirmed message, TP_1 creates the l new token and stores their token IDs in AA_{new} by sending an update_account(t^1_{new}, ..., t^l_{new}) message to P_{new}'s account holder set AHS_{new} using Algorithm 4.1.

Account Initialisation

Algorithm 4.4 Aggregation Account Initialization

This algorithm is used as sub-part by Algorithm 4.3 in order to initialise the aggregation account at all peers of the account holder set.

1. P_{AH1} receives an init_aggregation_account(AA^{ID}_{new}) from a trusted peer TP.
2. P_{AH1} creates a create_aggregation_account message(AA^{ID}_{new}), adds its peerID to the message, sets its hop counter to 1, and forwards the message to its successor on the DHT, $succ(P_{AH1})$.
3. P_{AH1} remembers the hop counter as its own position within the account holder set.
4. Whenever a peer P_s receives a create_aggregation_account message,
    1. P_s checks if it received this message before. If so it sets $AS = h$ and proceeds to step 4.e.i.
    2. It instantiates a new aggregation account for AA^{ID}_{new}.
    3. It adds its peerID to the message and increases the message's hop counter h by one.
    4. It remembers the hop counter as its own position within the account holder set.
    5. Let AS be the preferred account holder set size in the p2p system.
        1. If $h = AS$ then
            - P_s creates an aggregation_account_complete message containing the list of peerIDs from the received create_aggregation_account message.

- It remembers the list of peerIDs in the aggregation account.
- It sends this message to the peerID preceding its own peerID in the list of peerIDs.

2. else, P_s forwards the create_aggregation_account to its successor on the DHT, $succ(P_s)$.

5. Whenever a peer P_p receives an aggregation_account_complete message it
   - remembers the list of peerIDs contained in the message in the aggregation account.
   - it send the aggregation_account_complete message to the peerID preceding its own peerID in the list of peerIDs.
6. When P_{AH1} receives the aggregation_account_complete message it remembers the list of peerIDs contained in the message in the aggregation account. Then, it sends an account_confirmed message to TP.

D.1.1.2 Detection of Replica Number

In order to check if the account holder set is still complete, Algorithm 4.5 is applied. The algorithm can be initiated by any account holder. In order to keep track of an aggregation account the algorithm needs to be executed periodically. Thus, any account holder that did not receive a *detect_AHSS*-message for a specific time span will initiate Algorithm 4.5. The algorithm uses reliable authenticated connections, as all account holders must know each other and anonymity is not desired within an account holder set.

As explained in Algorithm 4.4, each account holder holds a list of all current account holders in the set. The first step of P_{AH_i}, the initialising peer of Algorithm 4.5, is to announce its know last status of the account holder set to all set members. In order to do that peer P_{AH_i} send a *detect_AHSS*-message containing the relevant status information (table with account holders and their last time active) to all known account holders (step 1 and step 2). There are three options for the result to these messages (step 3). If the account holder is offline the message is lost. If the receiver is online but not an account holder any more, it deletes itself from the account holder table contained in the message. Further, it checks if it has more recent information that can be added to the table. However this is unlikely, as the peer should have received less current information about the account holder set than the initialiser. In the third option the message receiver is still an account holder. It will add any further up-to-date information to the account holder table.

The updated account holder table is sent back to P_{AH_i} using a *detected_AHSS*-message. The message contains a time stamp when it was sent. Further, each peer having an additional account holder in the table will forward the *detect_AHSS*-message to it. These account holders will also respond to P_{AH_i} with a *detected_AHSS*-message.

P_{AH_i} collects the *detected_AHSS*-messages (step 4). As reliable authenticated connections are used for communication within the account holder set, it is assumed that an account holder is offline if it does not respond to the *detect_AHSS*-message. P_{AH_i} extracts the account holder tables from the received *detected_AHSS*-messages and creates an updated account holder table (step 5). In order to do that P_{AH_i} has first to calculate potential differences between its local clock and the respondees' local clocks, as these influence the time stamps in the account holder tables. The differences are calculated using the message time stamps created in step 3. (This is used for potential large differences in the account holders' clocks. Changes in the account holder table happen due to churn. Therefore, small clock variations can be tolerated). P_{AH_i} modifies the received account holder tables by adding the difference in the local time to it. Then, P_{AH_i} modifies its own account holder table by adding any new account holders received and updating the "last time active"-entries according to the received responses.

P_{AH_i} now sends the updated account holder table to all actual account holders using *confirm_AHS*-messages (step 6). If the account holder table shows that the account holder set currently has less

members than the preferred account holder set size, P_{AH_i} also initialises the execution of Algorithm 4.6 with a subsequent 4.8. This will lead to an optimal account holder size and the correct position of it on the DHT.

Algorithm 4.5 Detection of Current Account Holder Set Size

This algorithm is used by any account holder in order to detect the current size of the account holder set it belongs to.

1. An account holder P_{AH_i} creates a detect_AHSS(AA^{ID}) message. It adds a table to the message that contains the account holders P_{AH_i} believes are responsible for the aggregation account AA^{ID} and the time the account holders have been active the last time.
2. P_{AH_i} sends the detect_AHSS(AA^{ID}) to all account holders in the table (apart from itself).
3. Each peer P_j receiving a detect_AHSS(AA^{ID}) message checks weather it is account holder for aggregation account AA^{ID}.
   - If P_j is account holder for this aggregation account, then,
     - P_j extracts the account holder table for aggregation account AA^{ID} from the detect_AHSS(AA^{ID}) message.
     - P_j adds all peers missing in the account holder table to it. It remembers the peers it added to the table.
     - P_j marks all account holders in the table that are not account holders for this account any more. The mark is the time when the peer left the account holder set.
     - P_j forwards the updated detect_AHSS(AA^{ID}) message to the peers it added to the account holder table.
     - P_j responds to P_{AH_i} with an detected_AHSS(AA^{ID}) message, containing the updated account holder table and a time stamp.
   - Else,
     - P_j extracts the account holder table for aggregation account AA^{ID} from the detect_AHSS(AA^{ID}) message.
     - P_j removes itself from the account holder table.
     - P_j responds to P_{AH_i} with an detected_AHSS(AA^{ID}) message, containing the updated account holder table and a time stamp.
4. P_{AH_i} collects all detected_AHSS(AA^{ID}) messages.
5. P_{AH_i} extracts all account holders from the received detected_AHSS(AA^{ID}) messages and creates an updated account holder table:
   1. for each received detected_AHSS(AA^{ID}) messages send by P_s do
      1. $\Delta t_s = t_r - t_s$, where t_r is the local time when the message was received, t_s is the local time when the message was sent by P_s.
      2. for each entry e in the received account holder table do
         A. $e.t = e.t + \Delta t_s$, where $e.t$ is the last-time-active of the entry.
   2. P_{AH_i} creates a new account holder table from the received responses.
6. P_{AH_i} creates a confirm_AHS(AA^{ID}) message containing the updated account holder table and sends it to all peers in the table.

7. If the account holder table contains less entries than the preferred account holder set size, then
   - P_{AH_i} executes Algorithm 4.6 with a subsequent Algorithm 4.8.

D.1.1.3 Detection of Correct Account Holder Set Position

The algorithm determines if the account holder set should be moved without compromising the account holder set's position on the DHT. As described in Section 4.2.1.5 each account holder knows its position in an account holder set. The detection of the correct account holder position must be led by the first account holder in the set. Therefore, any other account holder P_{AH_i} initialising the algorithm must request the check of the account holder position from the first peer using a *check_account_position_request*-message (step 1). When the first account holder receives the message it replies with a *checking_account_position*-message, in order to inform the initialiser that the algorithm is executed (step 2). If the first account holder cannot be reached, P_{AH_i} tries to send the *check_account_position_request*-message to the other account holders it knows. This way, the first account holder will be found (step 3).

The next steps of the algorithm serve the purpose of counting the hops on the DHT between the first account holder and the peer responsible for the aggregation account ID AA^{ID}, $P_{AA^{ID}}$. However, it must be concealed which peer is collecting this information, as this would reveal the aggregation account's position on the DHT. That is, the message must be sender anonymous. In order to do that the first account holder P_{AH_1} creates a *request_hop_count*-message. This message contains a hopcounter that initially takes a random value. Due to this random value a peer receiving the *request_hop_count*-message cannot determine how many hops the message has be forwarded already on the DHT. Further, the message contains a unique query ID, in order to identify it when the message reaches the initial sender again. P_{AH_1} will send the *request_hop_count*-message to $P_{AA^{ID}}$. In order to conceal the sender it will use a UDP-based message. This peer will increase the hopcounter by one and forward the message to its successor on the DHT. The successor will do the same. This is repeated until the message reaches again P_{AH_1}. Using the message's query ID P_{AH_1} identifies the message as its own. By subtracting the hop counter's current value from its initial value P_{AH_1} can determine how many hops it is away from the peer responsible in the DHT for the aggregation account ID. If this value differs from the account shift value x, then P_{AH_1} initialises Algorithm 4.8 for moving the aggregation account.

There is the possibility that a peer is not increasing the hop counter by one but is modifying it in a different way. Then there are two options. Either P_{AH_1} recognises the deviation of protocol because the result does not make sense. The other option is that the result deviates just by a few hops from the actual value, which cannot be recognised. This is without effects as the account moving algorithm, Algorithm 4.8, is independent of this result.

A potential problem of sender anonymous messages is Denial of Service attacks. In order to avoid that identified messages can be used, where the first message is not sent directly to $P_{AA^{ID}}$, but indirectly over a trusted peer. $P_{AA^{ID}}$ will not be able to determine the sender because the trusted peer appears as sender in the message it receives.

Algorithm 4.6 Detection of correct account holder set position

This algorithm is used by any account holder peer in order to detect if the first account holder is still located at x hops distance from the peer that is responsible for the aggregation account ID in the DHT.

- Let P_{AH_i} be an account holder for aggregation account AA^{ID}, where i represents the account holders position in the account holder set. P_{AH_i} sets variable $j = 1$.

1. If P_{AH_i} is not the first account holder in the account holder set ($i \neq 1$), it creates a check_account_position_request(AA^{ID}) message and will send it to the first account holder in the account holder set P_{AH_j}.
2. Any peer receiving a check_account_position_request(AA^{ID}) message will
    1. forward the message to the first account holder in the account holder set, if it is not the first account holder in the set.
    2. will create as response to P_{AH_i} a checking_account_position(AA^{ID}) message P_{AH_i}, if it is the first account holder in the account holder set P_{AH_1}.
3. If P_{AH_i} does not receive a checking_account_position(AA^{ID}) message within a specific time period,
    1. it will assume that this peer went offline.
    2. it set variable $j = j + 1$.
    3. If $j < i$ it will send the check_account_position_request(AA^{ID}) message to account holder P_{AH_j}.
    4. Else it will continue will consider itself to be the first account holder of the account holder set and continue with step 4.
4. P_{AH_1} will
    1. create a request_hop_count message containing a hop counter set to a random value and a query ID.
    2. P_{AH_1} will remember the query ID with the corresponding hop counter's value.
    3. P_{AH_1} will send the message to $P_{AA^{ID}}$ that is responsible for AA^{ID} in the DHT.
5. Any peer P_a receiving a request_hop_count message will increase the message's hop counter by one.
6. P_a checks, if it sent the request_hop_count message using the contained query ID.
    - If it did not sent the message, P_a will increase the message's hop counter by one and forward it to its successor in the DHT.
    - If it sent the message, it will subtract the initial hop counter value from the received hop counter value. The result HC is the the number hops the peer is away from $P_{AA^{ID}}$.
7. If $HC \neq x$ then P_{AH_1} initialises Algorithm 4.8 for moving the aggregation account.

D.1.1.4 Account Holder Set Locking

Before an account can actually be moved, it has to be ensured that the account holder set is not processing any *aa_write_requests* in parallel. Otherwise, inconsistencies within the account holder set cannot be avoided. An *aa_write_request* is used to add new accounting information to an aggregation account (see Algorithm 4.11). The challenge to solve is that even in the presence of competing lock requests from different peers an unanimous result is achieved. In order to achieve this, a variation of the Strawman Protocol presented in (LLZ04) is applied.

First, the peer requesting a lock P_{AH_X} creates a *request_account_lock*-message, which it forwards to all account holders of aggregation account AA^{ID} (step 1). The account holders receiving the message have

to check, if the lock is possible or not. A lock is not possible, if it is already locked by another account holder or if another account holder has requested a lock earlier, however the lock is not active yet (step 2). If a lock is possible the account holder responds to all other account holders with an *account_locked* message. To this message it attaches a list of the open write requests (L_{WR}). This is required, as the account holders might receive write request in a different order and it is important that a locked account has a consistent view on the processed write requests.

Each account holder (including P_{AH_X}) receiving *account_locked*(AA^{ID}, locked, L_{WR})-messages from more than half of the account holders before this process times out, considers the account as locked for P_{AH_X} (step 3). It executes the write requests necessary for locking a consistent account holder set. When finished they inform P_{AH_X} that the lock is active by sending an *account_lock_confirmed*-message to P_{AH_X} containing the list of processed and still open write requests L'_{WR_Y} (step 4). P_{AH_X} combines the received lists L'_{WR_Y} and sends it to all account holders that have still an inconsistent view on the list. These peers will again answer with a *account_lock_confirmed*-message.

When all account holders finally have a consistent view on which write request should have been processed and which not, P_{AH_X} finally will execute the operations for which the aggregation account was locked, e.g., an account movement (step 5).

If P_{AH_X} does not receive the required number of *account_lock_confirmed*-messages, it cannot acquire the lock for the aggregation account and is sending an *account_lock_cancelled*-message in order to inform the account holders that the lock request was not successful and is not maintained. If required, it will try a random time later again to request a lock (step 6). A lock ends if the peer owning the lock sends an account_lock_release-message.

Algorithm 4.7 Account Holder Set Locking

This algorithm is used by any account holder peer in order to lock an account for writing new data in it while account management operations take place. Account holder P_{AH_X} wants to request a lock on the account holder set for aggregation account AA^{ID}.

1. P_{AH_X} creates a request_account_lock(AA^{ID}) message. It forwards the request_account_lock(AA^{ID}) message to all account holders for account AA^{ID}.
2. Whenever an account holder P_{AH_Y} receives a request_account_lock(AA^{ID}) message,
    1. P_{AH_Y} checks if the account AA^{ID} is already locked. If so, P_{AH_Y} responds to P_{AH_X} with an account_locked(AA^{ID}, already_locked) message. Break.
    2. P_{AH_Y} checks if it responded already to another unfinished lock request. If so, P_{AH_Y} responds to P_{AH_X} with an account_locked(AA^{ID}, lock_already_requested) message. Break.
    3. P_{AH_Y} creates a list of outstanding aa_write_requests, denoted L_{WR}. It responds to all account holders with an account_locked(AA^{ID}, locked, L_{WR}) message.
3. Each account holder P_{AH_y} collects the account_locked messages. If it receives more than $AHSS/2$ account_locked(AA^{ID}, locked, L_{WR}) messages,
    1. P_{AH_Y} executes all necessary aa_write_requests in order to achieve an consistent account holder set status. P_{AH_Y} marks the processed aa_write_requests in L_{WR}. The resulting list is denoted L'_{WR}.
    2. P_{AH_Y} sends an account_lock_confirmed(AA^{ID}, P_{AH_X}, L'_{WR_Y}) to P_{AH_X}.
4. If P_{AH_X} received more than $AHSS/2$ account_lock_confirmed(AA^{ID}, P_{AH_X}, L'_{WR_Y}) messages before the process times out,
    1. it checks of the received L'_{WR_Y} are consistent. If not,
        1. it chooses $L''_{WR} = \bigcup L'_{WR_Y}$

2. it sends a account_locked(AA^{ID}, locked, L''_{WR}) message to the inconsistent P_{AH_Y}.

5. P_{AH_X} executes all necessary operations that required the lock.

6. If P_{AH_X} received less than $AHSS/2$ account_lock_confirmed(AA^{ID}, P_{AH_X}, L'_{WR}) messages, P_{AH_X} sends a account_lock_cancelled(AA^{ID}) message to all account holders and waits for a random time period and restarts this algorithm.

7. In order to release a lock, P_{AH_X} sends an account_lock_release(AA^{ID}) message to all account holders.

D.1.1.5 Account Movement

The account movement algorithm is used for two purposes. First, it moves an aggregation account to the correct location on the DHT. Second, it creates a subsequent account holder set with the correct size. In order to achieve this the algorithm is split into two parts. The first part verifies the location of the first account holder. The second part actually moves the aggregation account to the new position. The algorithms are similar to the account creation described in Section 4.2.1.5.

The first part, Algorithm 4.8, is executed by the first account holder of the set, P_{AH_1}. First, the consistency of all account holders must be ensured (step 1). Otherwise, during the account movement existing inconsistencies could increase.

The correct location of the account holder set is determined by a trusted peer, as this part of the algorithm reveals some part of the DHT. This knowledge should not be revealed to normal peers as here a higher chance for misuse is given. Accordingly, P_{AH_1} sends a *request_account_movement*-message to a trusted peer TP. The message contains the account's account shift value x, as only account holders know this value (step 2). TP will lookup the peer responsible for the aggregation account ID in the DHT, P_C (step 4). Then, TP finds the first peer of the correct account holder set using the same multiple step processes as described in Algorithm 4.3 (steps 5 - 9). Finally, TP sends P_{AH_1} a peer ID (P_x) that lies within the new first account holders ID range contained in a *account_movement_result*-message.

Algorithm 4.8 Detect New Account Position

This algorithm determines the correct position for an aggregation account.

1. The current first account holder P_{AH_1} executes the consistency algorithm 4.12.

2. P_{AH_1} creates a request_account_movement(AA^{ID}, x) message and sends it to a trusted peer TP.

3. TP receives the request_account_movement(AA^{ID}, x) message.

4. TP looks up the peer responsible for AA^{ID}, denoted P_C.

5. TP randomly picks r values y, where $1 + 2r + \sum_{i=1}^{r} y_r = x$.

6. Set $P_k = P_C$.

7. For $i = 1$ to r do:

    1. Set $P_i = P_k$.
    2. TP looks up the P_i's successor on the DHT, P_j.
    3. TPsends request_peer message containing $(y_i - 1)$ to P_j.

4. P_j forwards the request_peer message to its $(y_i - 1)$-th successor, P_m.
5. P_m responds to TP with its successor's peerID, P_k.

8. P_k is the peer with $x - 1$ hops distance to P_C.
9. TP adds a small value to P_k's peer ID to create a value that lies within the P_k's successor's ID range, denoted P_x.
10. TP creates an account_movement_result(P_x) message and sends it to P_{AH_1}.

Now, the current first account holder, P_{AH_1}, will administer the moving of the account holder set to its new position. It receives the peerID P_x from a trusted peer (step 1). If this peerID lies within its own ID range, P_{AH_1} is also the first account holder in the new account holder set. Else, P_{AH_1} has to lookup the peer responsible for P_x. This peer is denoted P_n. P_{AH_1} will send a *new_first_account_holder*-message to P_n,containing the aggregation account ID AA^{ID} as well as the list of the current account holders. (step 3). P_n has now to determine the new account holder set.

It sends a *shift_aggregation_account*-message, containing a hop counter set to 1 and its own peerID, to its successor in the DHT (step 4). The peerID is the first entry of a list that will be used to collect the peerID of all new account holders.

The successor P_s receiving the *shift_aggregation_account*-message will increases the hop counter by one, add its peerID to the list, and remember the hop counter's value as its own position in the account holder set. Then it forwards the message to its successor on the DHT (step 6). This stops if either the hop counter has reached the preferred account holder set size or if a peer receives the message again, that has received the message before. The latter case means that the p2p system has only very few online peers and the message has traversed the complete DHT ring. Then, P_s sets the account holder set size to the current hop counter's value. The new account holder set is complete now. All the new account holders must now be informed about the composition of the new account holder set. Therefore, the last peer in the new account holder set will create a *shifting_aggregation_account*-message that contains the list of the new account holders. It will send this message to all new account holders (step 6f).

A peers P_p receiving the *shifting_aggregation_account*-message will remember the list of new account holders (step 7). If it is also an account holder in the current set, then no further actions are required. Only if P_p is not an account holder in the current set it needs to retrieve now the account information from such a peer. For that it will choose the peer in the current set that is at the same account position as P_p in the new set. If this position was not occupied, P_p chooses a random account holder from the current set. This will distribute the work load among the current account holders. Further, it ensures that a potential incorrect account replica will not be multiplied in the new set.

Now the account information transfer needs to be performed. However, it must be ensured that only peers permitted as account holders will receive the information. Therefore, the new account holders will forward the *shifting_aggregation_account*-message to the current account holders that were selected for the information transfer (step 8). The current account holders will transfer their account information using *account_transfer*-messages. When the transfer was successful, the new account holders will respond with a *transfer_complete*-message. Then, the current account holders can delete the account.

In order to ensure that only the selected peers are taking place in the account movement, all communication uses reliable authenticated connections.

Algorithm 4.9 Move Account to New Position

This algorithm moves an aggregation account to the correct position on the DHT.

1. Account holder P_{AH_1} receives an account_movement_result(P_x) message.
2. P_{AH_1} waits until Algorithm 4.12 is completed.

3. If P_x lies not in P_{AH_1}'s ID range,
    1. then
        1. P_{AH_1} looks up the responsible peer for P_x in the DHT, denoted as P_n.
        2. P_{AH_1} creates a new_first_account_holder(AA^{ID}, P_x) message and adds a list of the current account holders to it.
        3. P_{AH_1} sends the new_first_account_holder(AA^{ID}, P_x) to P_n.
    2. else $P_n = P_{AH_1}$.
4. P_n creates a shift_aggregation_account(AA^{ID}) message, adds the list of current account holders to the message and it adds a list of new account holders to the message containing its own peerID. It sets its hop counter to 1, and forwards the message to its successor on the DHT, $succ(P_n)$.
5. P_n remembers the hop counter as its own position within the account holder set.
6. Whenever a peer P_s receives a shift_aggregation_account message,
    1. P_s checks if it received this message before. If so it sets $AS = h$ and proceeds to step 6.6.
    2. P_s checks if it is already account holder for account AA^{ID}. If not, it instantiates a new aggregation account for AA^{ID}.
    3. It adds its peerID to the message and increases the message's hop counter h by one.
    4. It remembers the list of current account holders.
    5. It remembers the hop counter as its own position within the new account holder set.
    6. Let AS be the preferred account holder set size in the p2p system.
        1. If $h = AS$ then
            - P_s creates an shifting_aggregation_account(AA^{ID}) message containing the list of new account holders from the received shift_aggregation_account message.
            - It remembers the list of new account holders in the aggregation account.
            - It sends this message to all peers in the new account holder list.
        2. else, P_s forwards the shift_aggregation_account to its successor on the DHT, $succ(P_s)$.
7. Whenever a peer P_p receives an shifting_aggregation_account(AA^{ID}) message it
    1. remembers the list of new account holders contained in the message in the aggregation account.
    2. if P_p is not an account holder in the current account holder set, then
        1. P_p chooses from the list of current account holder the peer with the account holder set position equal to its own account holder set position in the new account holder set, denoted P_t
           If this position is not assigned in the current account holder set P_p chooses a random peer from the current account holder set as P_t.
        2. P_p creates a request_account_transfer(AA^{ID}) message and sends it to P_t.
8. When P_n receives the shifting_aggregation_account(AA^{ID}) message it forwards it to all peers in the current account holder list.
9. Whenever a peer P_t receives a request_account_transfer(AA^{ID}) message from a peer P_p contained in the new account holder list, P_t creates an account_transfer(AA^{ID}) message, containing all account data of account AA^{ID} and sends this message to peer P_t.

10. Whenever a peer P_p receives an account_transfer(AA^{ID}) message and stores the contained account information successfully, P_p sends a transfer_complete(AA^{ID}) message to P_t.

11. Whenever a peer P_t receives a transfer_complete(AA^{ID}) message, it removes the aggregation account AA^{ID}.

D.1.1.6 Graceful Aggregation Account Handover

In order to avoid a complete new account assignment when an account holder leaves the p2p system an account holder should handover the accounts it hosts to another peer. Whenever an account holder plans to leave the system it will execute Algorithm 4.10 in order to do a clean log off. This is called Graceful Handover. The peer leaving the p2p system P_o has to do the graceful handover for all the aggregation accounts it hosts (step 2).

First, P_o first informs all account holders about its planned leave, using a *leaving_system*-message. When an account holder leaves, it means that the account holder set must be extended at the end of the set. If it would add a new peer the front, the aggregation account was shifted one hop towards the peer responsible for the aggregation account ID on the DHT. Therefore, the last account holder in the set P_l is sending an *account_handover*-message to its successor on the DHT, denoted P_m. P_m will replace P_o in the account holder set. In order to ensure that the account is transferred to the correct peer, P_m will now contact P_o using *handover_peer*-message. This message serve as authentication to P_o that it should transfer its account to P_m. P_o uses an *account_transfer*-message to transfer all account information to P_m. After a successful account transfer P_m will inform all account holders including P_o that it is now storing the aggregation account using a *transfer_complete*-message. All account holders will update their account holder list and P_o may leave the p2p system.

Algorithm 4.10 Graceful Aggregation Account Handover

This algorithm is executed by an account holder that plans to leave the p2p system in order to transfer its accounts to other peers.

1. Peer P_l plans to leave the p2p system.
2. For each aggregation account P_l hosts do
    1. P_o sends a leaving_systems(P_o, AA^{ID}) message to all account holders of account AA^{ID}.
    2. The last peer in the account holder set, denoted P_l, creates a account_handover(AA^{ID}, P_o) message
    3. P_l sends the account_handover(AA^{ID}, P_o) message to its successor on the DHT, denoted P_m.
    4. P_l sends a handover_peer(AA^{ID}, P_m) message to P_o.
    5. P_o creates an account_transfer(AA^{ID}) message.
    6. P_o sends the account_transfer(AA^{ID}) message to P_m.
    7. P_m creates a transfer_complete(AA^{ID}) message to all account holders of aggregation account AA^{ID}, including P_o.
    8. all account holders for aggregation account AA^{ID} update their account holder list.
3. P_o leaves the p2p system.

D.1.2 Information Storage

D.1.2.1 Storing Information in an Account Holder Set

Algorithm 4.11 Post Account Information at an Account Holder Set

Peer P_A needs to contact account aggregation account AA^{ID} for requesting account information or posting account information. This algorithm ensures, that the message is delivered to the account holder set, and that the responses are delivered to peer P_A.

1. Peer P_A creates a aa_request message. This is either an aa_read_request(AA^{ID}, $query$) message for requesting account information. Or it is an aa_write_request(AA^{ID}, $post$) message for posting account information.
2. P_A looks up the peerID of P_C, the peer responsible for AA^{ID} in the DHT.
3. P_A sends the aa_request message to P_C.
4. Each peer P_i receiving an aa_request message,
    1. P_i checks if the message signee is permitted to request or post account information for account AA^{ID}. If not, P_C drops the message and files a reputation report.
    2. If P_i is permitted to send the aa_request message, P_i checks if it hosts account AA^{ID}.
        1. If P_i hosts account AA^{ID}, P_i transforms the aa_request message into an enqueue_aa_request(AA^{ID}) message. P_i forwards the enqueue_aa_request message(AA^{ID}) to all account holders for account AA^{ID}. It enqueues the aa_request.
        2. If not, P_i forwards the aa_request message to its successor on the DHT.
5. Whenever an account holder $P_{AH_{ID}}$ for account AA^{ID} receives an enqueue_aa_request(AA^{ID}) message it will enqueue it in the account queue and process it when appropriate.
    1. $P_{AH_{ID}}$ will create an aa_response(AA^{ID}) message.
6. If the aa_response message is of type aa_write_response, then
    1. $P_{AH_{ID}}$ sends the response to P_{AH_1}, where P_{AH_1} is the peer that send the enqueue_aa_request(AA^{ID}) message.
    2. P_{AH_1} will collect all aa_response(AA^{ID}) messages.
        1. If P_{AH_1} receives more than $AHSS^{ID}/2$ consistent aa_response(AA^{ID}) messages, where $AHSS^{ID}$ is the current account holder set of aggregation account AA^{ID}.
            A. P_{AH_1} will lookup the peer responsible for AA^{ID} on the overlay, P_A.
            B. P_{AH_1} will send the aa_response(AA^{ID}) message to P_A.
            C. If P_{AH_1} received inconsistent aa_response(AA^{ID}) messages, it executes Algorithm 4.12.
        2. Else If P_{AH_1} receives less than $AHSS^{ID}/2$ aa_response(AA^{ID}) messages,
            A. P_{AH_1}will send an re-enqueue_aa_request(AA^{ID}) message to all account holders for account AA^{ID}.
            B. P_{AH_1}will execute Algorithm 4.5 and any further required account management algorithms.

3. Else If P_{AH_1} receives less than $AHSS^{ID}/2$ consistent aa_response(AA^{ID}) messages, it
   A. P_{AH_1} will send an re-enqueue_aa_request(AA^{ID}) message to all account holders for account AA^{ID}.
   B. P_{AH_1} executes Algorithm 4.12.

3. Each account holder peer P_{AH_X}
   1. After account management algorithms or the account consensus algorithm have terminated, P_{AH_X} processes a re-enqueue_aa_request(AA^{ID}) message form the FIFO-queue as P_{AH_1} starting at step 4.
4. Each peer P_C receiving an aa_response (AA^{ID}) message forwards it to P_A.

7. Else, $P_{AH_{ID}}$ sends the response to P_A.
8. An account holder P_{AH_X} receiving a re-enqueue_aa_request(AA^{ID}) message will
   1. halt processing events.
   2. enqueue the aa_request contained in the re-enqueue_aa_request(AA^{ID}) message at the first position of the FIFO-queue.
   3. After the next consistency algorithm (Algorithm 4.12) has been finalised, processing events is continued.

D.1.3 Consensus Mechanism

D.1.3.1 Account Holder Set Consensus Mechanism

Algorithm 4.12 Aggregation Account Consistency Algorithm

The algorithm ensures that all replicas in an account holder set store consistent information. The consistency algorithm is initialised by one quorum peer, P_{AH_1}. P_{AH_1} has successfully requested a lock for aggregation account AA^{ID} using Algorithm 4.7.

1. While there are inconsistencies in the account do
   1. P_{AH_1} creates an aggregation account summary S_1^{ID}.
   2. P_{AH_1} creates a request_consistency_check(AA^{ID}, account summary) message and sends it to all account holders.
   3. Whenever an account holder P_{AH_X} receives a request_consistency_check(AA^{ID}, account summary) message it
      1. creates an aggregation account summary S_X^{ID}
      2. compares the received account summary S_1^{ID} against its own one S_X^{ID} line by line.
      3. if there are any line inconsistencies or S_X^{ID} has additional lines in S_X^{ID}, P_{AH_X} creates a request_update(AA^{ID}, diff(S_1^{ID}, S_X^{ID})) message. P_{AH_X} sends the message to all account holders.
      4. If $S_1^{ID} = S_X^{ID}$, then P_{AH_X} creates a consistent_account(AA^{ID}) message and sends it to all account holders.

4. Each account holder P_{AH_Y} waits to receive the request_update(AA^{ID}, diff(S_1^{ID}, S_X^{ID})) messages or consistent_account(AA^{ID}) messages.
5. Each account holder P_{AH_Y} accepts line changes, if the simple majority of peers agree on this information.
6. Each account holder P_{AH_Y} accepts a new line in its account, if $> p_{nl}$% of all account holders store that line in their account.
7. Each account holder that stores a line that $< p_{nl}$% of all account holders also store, has to delete this line.

2. End While

D.2 Trusted Peers

D.2.1 Finding Trusted Peers

The algorithm to locate a trusted peer is described in Algorithm 4.13. The peer P_x is looking for the trusted peer next to ID ID_s. First it needs to lookup the peer P_s responsible for ID_s. To P_s it sends a *get-next_TP*-message to P_s. P_s will respond with the overlay address of the next trusted peer TP. If TP left in the meantime, then P_s will use this algorithm to retrieve the next trusted peer of TP's successor in the DHT before responding to P_x.

Algorithm 4.13 Locate Trusted Peer

This algorithm locates the first trusted peer after the overlay address ID_s on the system overlay. Each peer maintains a finger to the next trusted peer TP in the DHT. If the peer is a trusted peer itself, the finger points to itself.

1. P_x does a lookup on the DHT of ID_s. It receives P_s as return.
2. P_x creates a get-next-TP(P_x)-message and sends it to P_s.
3. Any peer P_t receiving the get-next-TP(P_x)-message will:
    1. If P_t is a trusted peer, P_t sends a next-TP(P_t) message to P_x.
    2. Else,
        1. If TP is still alive, P_t sends a next-TP(TP) message to P_x.
        2. Else,
            A. P_t runs this Algorithm for ID TP resulting in TP_{new}.
            B. sends a next-TP(TP_{new}) message to P_x.

D.3 Secure Aggregation Protocol

D.3.1 Protocol Details

Algorithm 4.14 Secure Token Aggregation

A peer SP swaps collected foreign tokens against new own tokens. The trusted peer creating the fresh tokens as well as the quorum peers signing the fresh tokens partially are selected randomly using information stored in SP's aggregation account. The account holders check that only the selected trusted peers take part in the aggregation process.

1. SP sends b foreign tokens to random peer TP_1using a aggregate_token(F_1, ..., F_b)-message.
2. TP_1 sends a request_account_stamp(AA_{SP}) message to SP's account holder set AHS_{SP}.
    1. AHS_{SP} calculates a hash value h_{SP} of the account information.
    2. AHS_{SP} uses Algorithm 4.13 to locate the next trusted peer of h_{SP} in the system overlay, TP_2.
    3. If $TP_2 = TP_1$, AHS_{SP}uses Algorithm 4.13 to locate the next trusted peer of inverse(h_{SP}) in the system overlay TP_2.
    4. AHS_{SP} sends an account_stamp_result(TP_2) message to TP_1.
3. TP_1 forwards the aggregate_token(F_1, ..., F_b)-message to TP_2.
4. TP_2 will act as aggregation administrator. TP_2 calculates the number of new token $N = A(F_1, ..., F_b)$ to be created. TP_2 creates n new token U_1, ..., U_n.
5. TP_2 sends the new tokens' issuing information to AHS_{SP} using a new_tokens(AA_{SP}, (U_1, ..., U_n)) message.
    1. AHS_{SP} check if the message was sent by TP_2. If not, a reputation report is filed against the sender.
    2. AHS_{SP} calculates a hash value h'_{SP} of the account information.
    3. l= h'_{SP}
    4. for $i = 1$to t
        1. AHS_{SP} uses Algorithm 4.13 to locate the next trusted peer of l in the system overlay, QP_i.
        2. $l = QP_i + 1$
    5. AHS_{SP} send a new_tokens_quorum(QP_1, ..., QP_t) message to TP_2.
6. TP_2 sends t fresh_tokens(SP, (U_1, ..., U_n)) message to QP_1, ..., QP_t.
7. Each quorum peer QP_1, ..., QP_tsends a new_partial_tokens(AA_{SP}, (U_1, ..., U_n)) message to AHS_{SP}.
    1. If AHS_{SP} receives new_partial_tokens(AA_{SP}, (U_1, ..., U_n)) messages from QP_1, ..., QP_t, then AHS_{SP} add the fresh tokens U_1, ..., $U_n$to AA_{SP}.
    2. If AHS_{SP} receives a new_partial_tokens(AA_{SP}, (U_1, ..., U_n)) messages from a different peer, AHS_{SP} files a reputation report against the sending peer.
    3. The quorum peers QP_1, ..., QP_t sign the fresh tokens U_1, ..., U_n partially.

8. The quorum peers QP_1, ..., QP_t send a new_tokens(P_1, ..., P_n) message to SP. SP creates n new tokens from P_1, ..., P_n.

E Supplementary Simulation Results

E.1 Account Holder Set Size Simulations

E.1.1 Summary of Results of Account Holder Set Size Simulations

Table E.1: Required Holder Set Sizes for Different Churn Models – Details

p_{gh}	d_{var}	k	$\tau_{\tilde{k}=3}$	$\tau_{\tilde{k}=4}$	$\tau_{\tilde{k}=5}$	$\tau_{\tilde{k}=6}$	$\tau_{\tilde{k}=7}$	$\tau_{\tilde{k}=8}$	$\tau_{\tilde{k}=9}$	$\tau_{\tilde{k}=10}$
Weibull										
0.9	1	6	0	14511.2	4.19E+06	6.01E+08	–	–	–	–
	$\frac{1}{2}$	6	139.25	60536.15	8.02E+06	5.97E+08	–	–	–	–
	$\frac{1}{3}$	6	839.05	125505.1	1.17E+07	5.93E+08	–	–	–	–
	$\frac{1}{4}$	7	4.2	2751.8	3.08E+05	1.76E+07	5.87E+08	–	–	–
0.5	1	7	91.3	6551.35	5.39E+05	2.32E+07	5.81E+08	–	–	–
	$\frac{1}{2}$	7	20.9	2001.8	8.59E+04	2.52E+06	4.87E+07	5.54E+08	–	–
	$\frac{1}{3}$	9	0	479.3	1.65E+04	3.81E+05	6.52E+06	7.49E+07	5.23E+08	–
	$\frac{1}{4}$	10	0	137.4	3.65E+03	6.81E+04	1.12E+06	1.28E+07	1.01E+08	4.90E+08
Mixed Log-normal										
0.9	1	6	21.1	16484.4	4.24E+06	6.01E+08	–	–	–	–
	$\frac{1}{2}$	6	301.1	66831	8.54E+06	5.96E+08	–	–	–	–
	$\frac{1}{3}$	7	47.2	2089.1	2.18E+05	1.49E+07	5.90E+08	–	–	–
	$\frac{1}{4}$	7	4.35	4554.2	3.85E+05	1.98E+07	5.85E+08	–	–	–
0.5	1	7	52.5	7318.5	5.56E+05	2.36E+07	5.81E+08	–	–	–
	$\frac{1}{2}$	9	0	92.5	4.60E+03	1.55E+05	3.59E+06	5.68E+07	5.44E+08	–
	$\frac{1}{3}$	9	0	545.75	2.13E+04	4.88E+05	7.74E+06	8.05E+07	5.16E+08	–
	$\frac{1}{4}$	9	44.3	2220.7	6.32E+04	1.10E+06	1.29E+07	1.01E+08	4.90E+08	–

* with $k = 9$ there happened a $\tilde{k} = 2$.
** with $k = 6$ there happened a $\tilde{k} = 2$.

This table summarises the simulation results for determining the required account holder set sizes k, where $\tilde{k}$ denotes the actual actual account holder set size in the simulation and τ denotes the accumulated time a specific actual account holder set size was observed on average.

E.1.2 Individual Results of Account Holder Set Size Simulations by Experiments

Table E.2: Detailed Simulation Results for Weibull Distribution, $d_{var} = 1$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0	0	0
4	14.5112	12.66929255	16.35310745
5	4186.18535	4134.405231	4237.965469
6	600599.3035	600547.7174	600650.8895

Table E.3: Detailed Simulation Results for Weibull Distribution, $d_{var} = 0.5$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.13925	0.065083433	0.213416567
4	605.3615	55.73625269	65.33604731
5	8015.91645	7954.948449	8076.884451
6	596723.4082	596660.7724	596786.0439

Table E.4: Detailed Simulation Results for Weibull Distribution, $d_{var} = 0.333$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.83905	0.456680494	1.221419506
4	125.5051	120.1931457	130.8170543
5	11678.8654	11583.06884	11774.66196
6	592994.7905	5928977.799	593091.801

Table E.5: Detailed Simulation Results for Weibull Distribution, $d_{var} = 0.25$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.0042	-0.0030618	0.0114618
4	2.7518	2.038542122	3.465057878
5	307.7595	293.8814196	321.6375804
6	17638.4362	17546.49684	17730.37556
7	586851.0483	586759.6963	586942.4003

Table E.6: Detailed Simulation Results for Weibull Distribution, $d_{var} = 1$, $p_{log-off} = 0.5$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.0913	-0.018932188	0.201532188
4	6.55135	5.71499812	7.38770188
5	538.80695	528.4459332	549.1679668
6	23232.5741	23087.52213	23377.62607
7	581021.9763	580873.8217	581170.1309

Table E.7: Detailed Simulation Results for Weibull Distribution, $d_{var} = 0.5$, $p_{log-off} = 0.5$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.0209	-0.000634609	0.042434609
4	2.0018	1.577086944	2.426513056
5	85.90765	81.34118568	90.47411432
6	2518.18265	2489.881911	2546.483389
7	48656.188	48489.10259	48823.27341
8	553537.699	553359.9735	553715.4245

Table E.8: Detailed Simulation Results for Weibull Distribution, $d_{var} = 0.333$, $p_{log-off} = 0.5$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0	0	0
4	0.4793	0.296143561	0.662456439
5	16.49105	14.98341095	17.99868905
6	381.4272	371.5331553	391.3212447
7	6521.73415	6475.609043	6567.859257
8	74945.12875	74752.42166	75137.83584
9	522934.7396	522723.302	523146.1771

Table E.9: Detailed Simulation Results for Weibull Distribution, $d_{var} = 0.25$, $p_{log-off} = 0.5$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0	0	0
4	0.1374	0.053829663	0.220970337
5	3.6524	3.047345097	4.257454903
6	68.1156	65.50443581	70.72676419
7	1121.5752	1106.302276	1136.848124
8	12811.54405	12730.55114	12892.53696
9	100565.3186	100324.2878	100806.3494
10	490229.6568	489919.3045	490540.009

Table E.10: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 1$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.0211	-0.006378506	0.048578506
4	16.4844	14.78385328	18.18494672
5	4239.9669	4192.853456	4287.080344
6	600543.5276	600496.4344	600590.6208

Table E.11: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 0.5$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.3011	0.13847708	0.46372292
4	66.831	63.63869262	70.02330738
5	8542.75385	8480.526971	8604.980729
6	596190.1141	596128.274	596251.9541

Table E.12: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 0.333$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.0472	-0.03225182	0.12665182
4	2.0891	1.586739654	2.591460346
5	218.34095	212.1255874	224.5563126
6	14896.78785	14792.12777	15001.44793
7	589682.7349	589579.2939	589786.1759

Table E.13: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 0.25$, $p_{log-off} = 0.9$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.00435	-0.000911203	0.009611203
4	4.5542	3.7869363	5.3214637
5	384.99785	376.2815899	393.7141101
6	19764.2178	19692.4969	19835.9387
7	584646.2258	584572.1543	584720.2973

Table E.14: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 1$, $p_{log-off} = 0.5$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.0525	0.013866984	0.091133016
4	7.3185	6.53659705	8.10040295
5	556.14745	545.4125728	566.8823272
6	23571.0399	23473.26605	23668.81375
7	580665.4417	580561.2539	580769.6294

Table E.15: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 0.5$, $p_{log-off} = 0.5$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0	0	0
4	0.0925	0.007521203	0.177478797
5	4.5964	3.955899984	5.236900016
6	154.63935	149.2204756	160.0582244
7	3588.95735	3559.67284	3618.24186
8	56793.534	56588.75167	56998.31633
9	544258.1804	544056.3023	544460.0585

Table E.16: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 0.333$, $p_{log-off} = 0.5$

		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0	0	0
4	0.54575	0.393253579	0.698246421
5	21.3146	19.4080752	23.2211248
6	488.2935	480.6382651	495.9487349
7	7736.7252	7697.447219	7776.003181
8	80473.56075	80293.53164	80653.58986
9	516079.5602	515891.3946	516267.7258

Table E.17: Detailed Simulation Results for Mixed Log-Normal Distribution, $d_{var} = 0.25$, $p_{log-off} = 0.5$

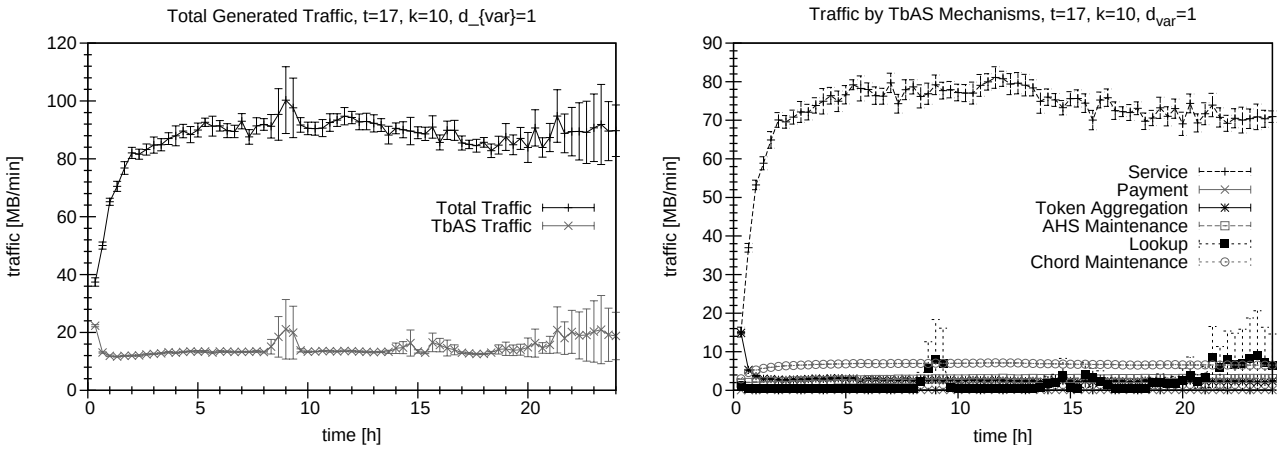
		Confidence interval (90%) [sec]	
Set size	Duration [sec]	Lower Bound	Upper Bound
3	0.0443	-0.001209189	0.089809189
4	2.2207	1.685776111	2.755623889
5	63.23645	60.18966383	66.28323617
6	1103.952	1088.993221	1118.910779
7	12907.32945	12849.57859	12965.08031
8	100665.5566	100482.7898	100848.3233
9	490057.6606	489846.6223	490268.6988

E.2 Token-based Accounting Scheme Simulations

E.2.1 Overall Traffic

E.2.1.1 Overall Traffic by Quorum Size

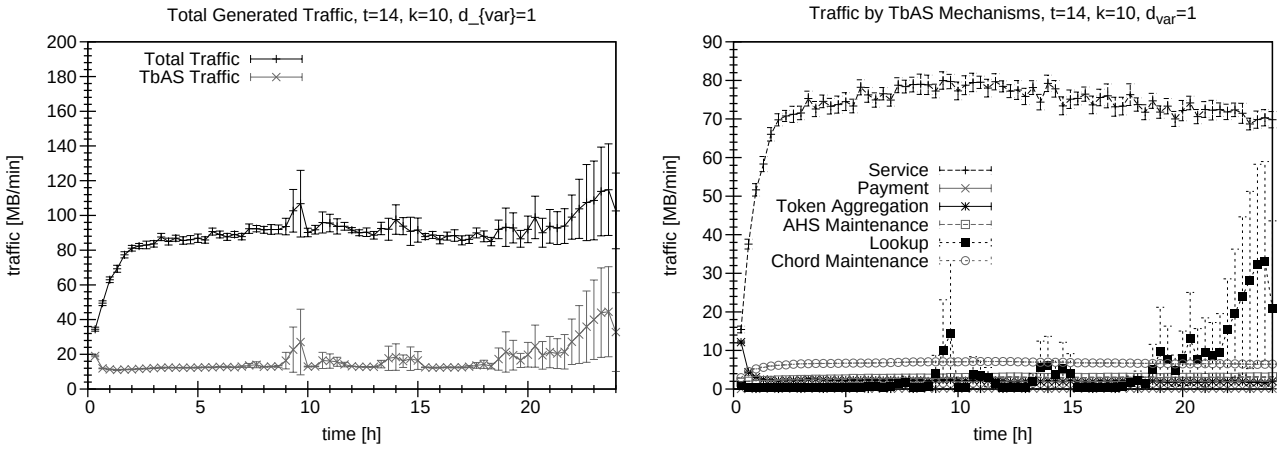
Overall Traffic for $t = 17$, $k = 10$, $d_{var} = 1$



(a) Complete traffic vs. accounting traffic (b) Traffic breakdown

Figure E.1: System-wide traffic for $t = 17$, $k = 10$, $d_{var} = 1$

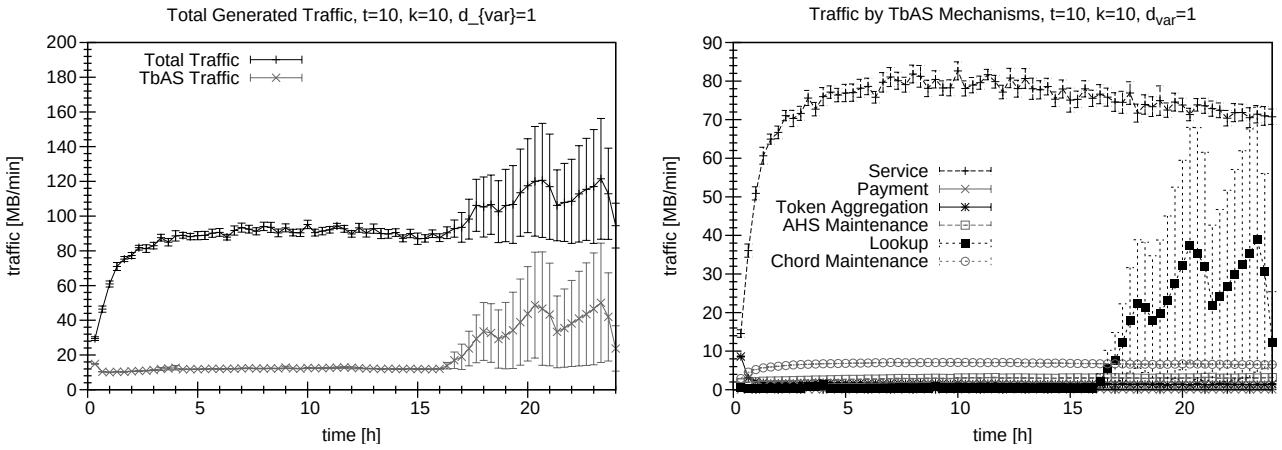
Overall Traffic for $t = 14$, $k = 10$, $d_{var} = 1$



(a) Complete traffic vs accounting traffic (b) Traffic breakdown

Figure E.2: System-wide traffic for $t = 14$, $k = 10$, $d_{var} = 1$

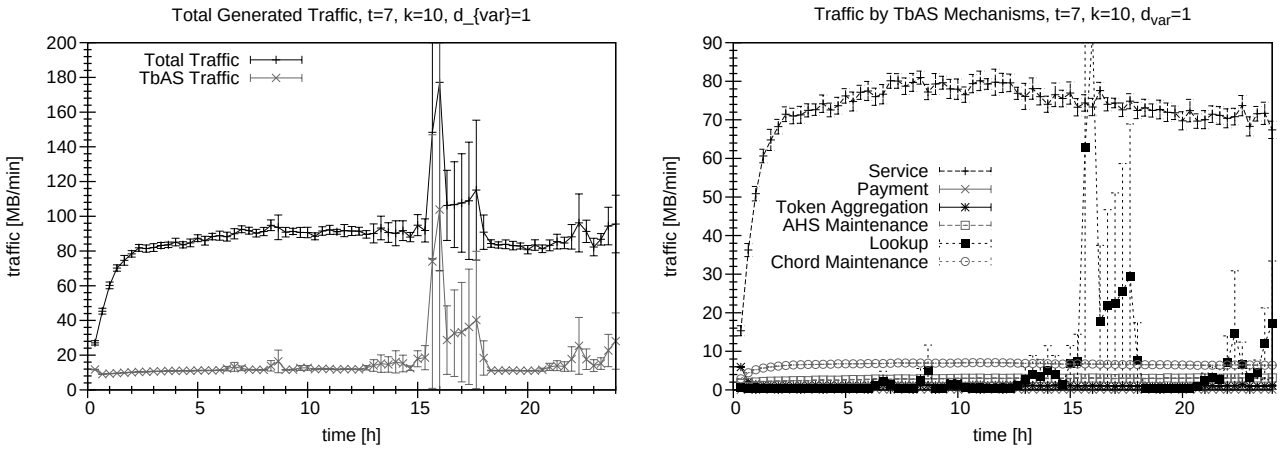
Overall Traffic for $t = 10$, $k = 10$, $d_{var} = 1$



(a) Complete traffic vs accounting traffic (b) Traffic breakdown

Figure E.3: System-wide traffic for $t = 10$, $k = 10$, $d_{var} = 1$

Overall Traffic for $t = 7$, $k = 10$, $d_{var} = 1$

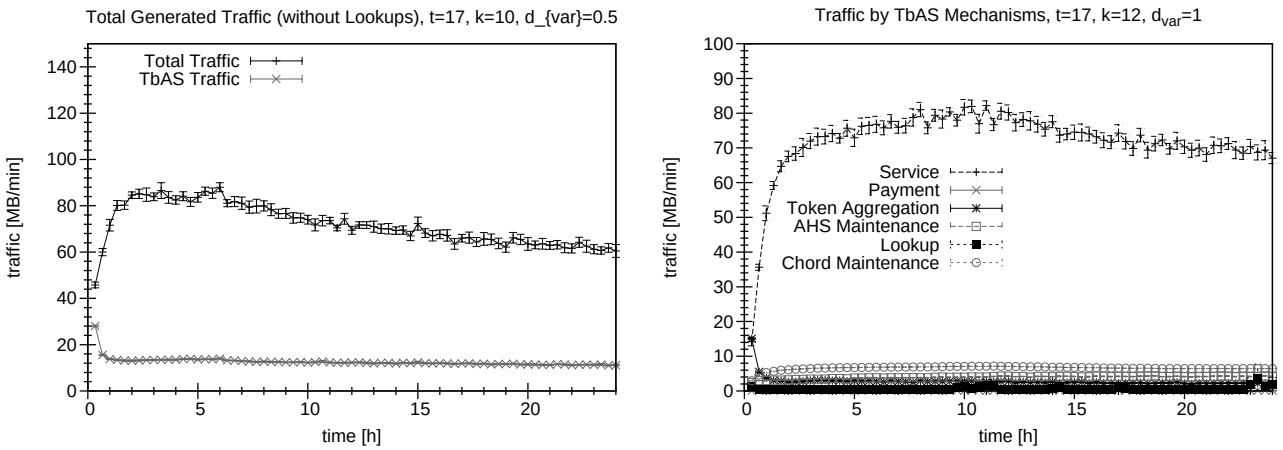


(a) Complete traffic vs. accounting traffic (b) Traffic breakdown

Figure E.4: System-wide traffic for $t = 7$, $k = 10$, $d_{var} = 1$

E.2.1.2 Overall Traffic by Account Holder Set Size

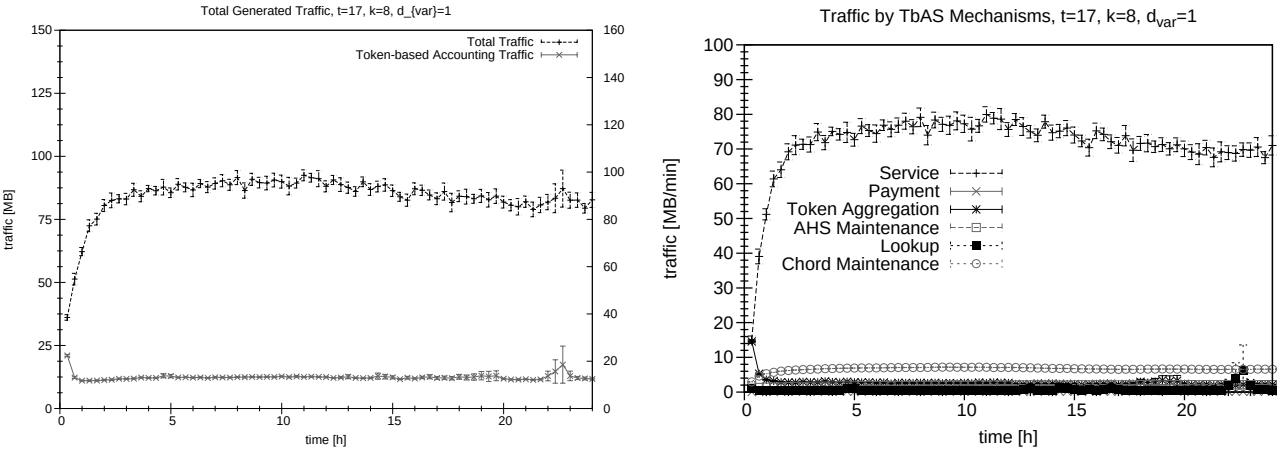
Overall Traffic for $t = 17$, $k = 12$, $d_{var} = 1$



(a) Complete traffic vs. accounting traffic (b) Traffic breakdown

Figure E.5: System-wide traffic for $t = 17$, $k = 12$, $d_{var} = 1$

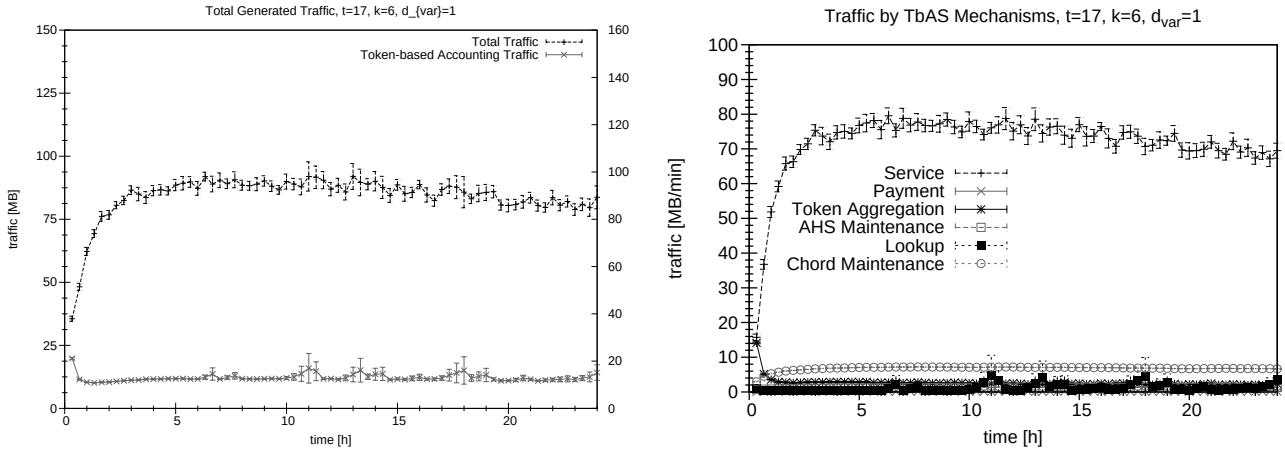
Overall Traffic for $t = 17$, $k = 8$, $d_{var} = 1$



(a) Complete traffic vs. accounting traffic (b) Traffic breakdown

Figure E.6: System-wide traffic for $t = 17$, $k = 8$, $d_{var} = 1$

Overall Traffic for $t = 17$, $k = 6$, $d_{var} = 1$

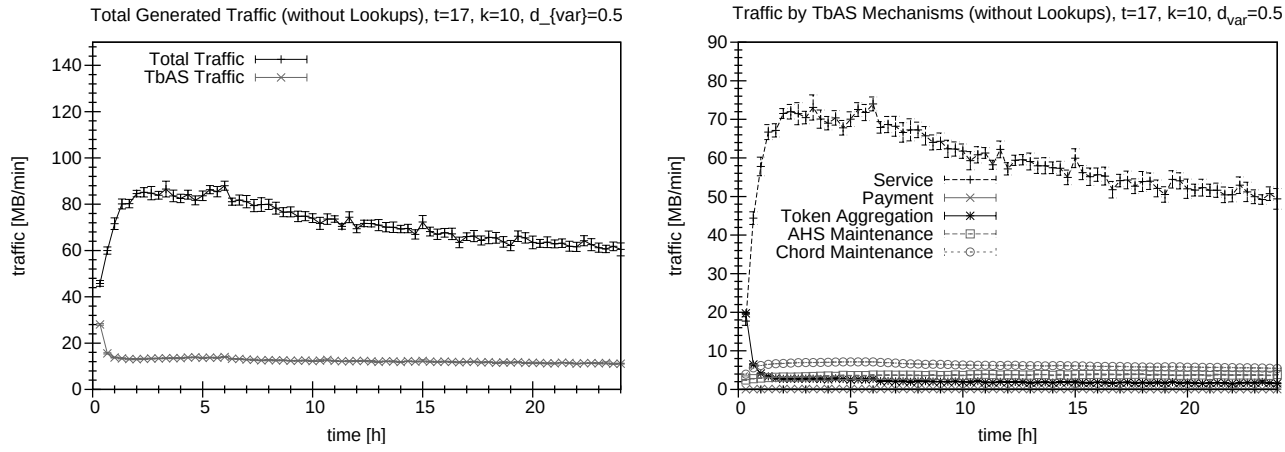


(a) Complete traffic vs. accounting traffic (b) Traffic breakdown

Figure E.7: System-wide traffic for $t = 17$, $k = 6$, $d_{var} = 1$

E.2.1.3 Overall Traffic by Churn Factor

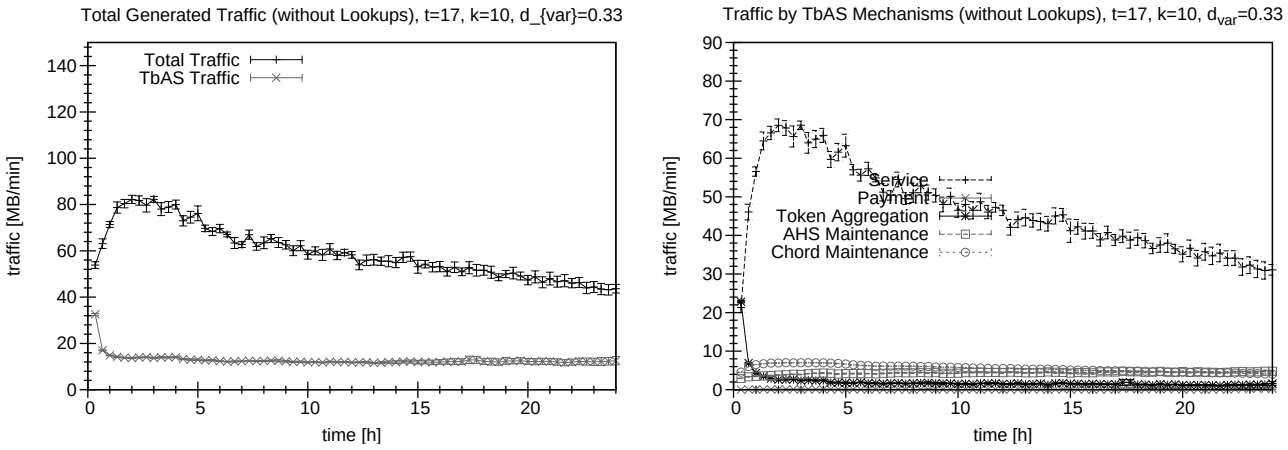
Overall Traffic for $t = 17$, $k = 10$, $d_{var} = 0.5$



(a) Complete traffic vs. accounting traffic (b) Traffic breakdown

Figure E.8: System-wide traffic for $t = 17$, $k = 10$, $d_{var} = 0.5$

Overall Traffic for $t = 17$, $k = 10$, $d_{var} = 0.33$

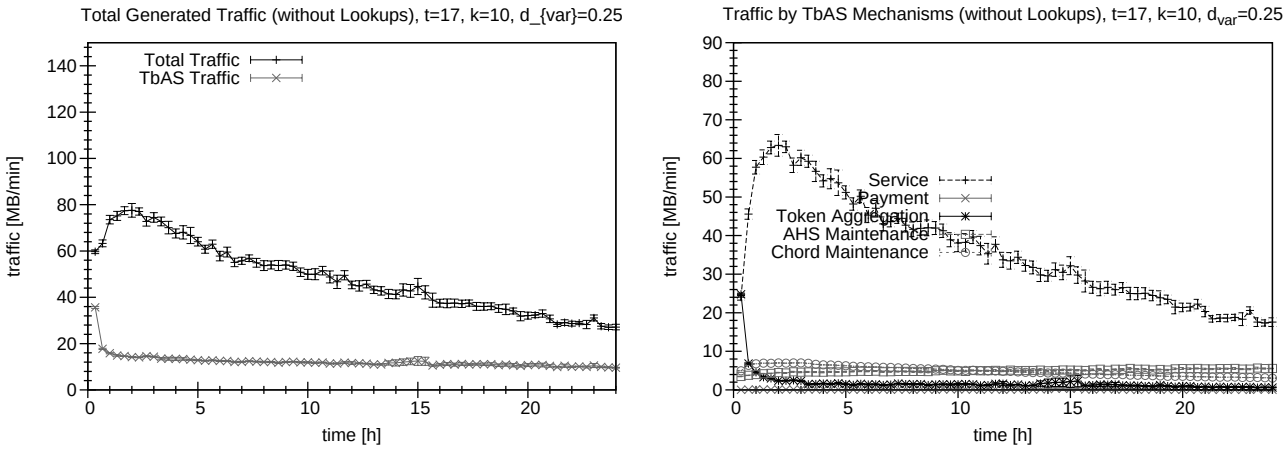


(a) Complete traffic vs. accounting traffic

(b) Traffic breakdown

Figure E.9: System-wide traffic for $t = 17$, $k = 10$, $d_{var} = 0.33$

Overall Traffic for $t = 17$, $k = 10$, $d_{var} = 0.25$



(a) Complete traffic vs. accounting traffic

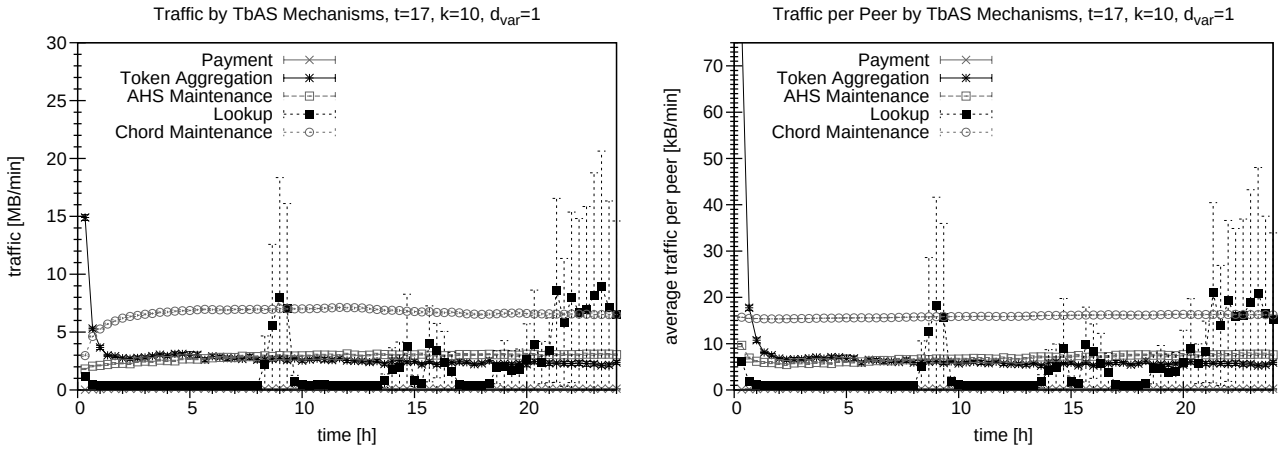
(b) Traffic breakdown

Figure E.10: System-wide traffic for $t = 17$, $k = 10$, $d_{var} = 0.25$

E.2.2 Traffic Breakdown

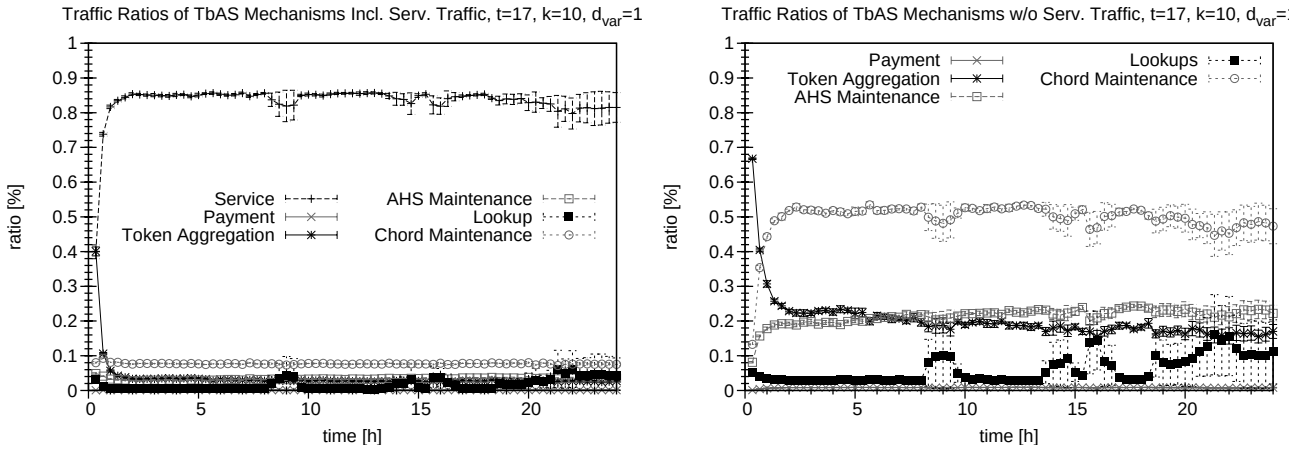
E.2.2.1 Traffic Breakdown by Quorum Size

Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 1$



(a) System-wide traffic (b) Average traffic per active peer

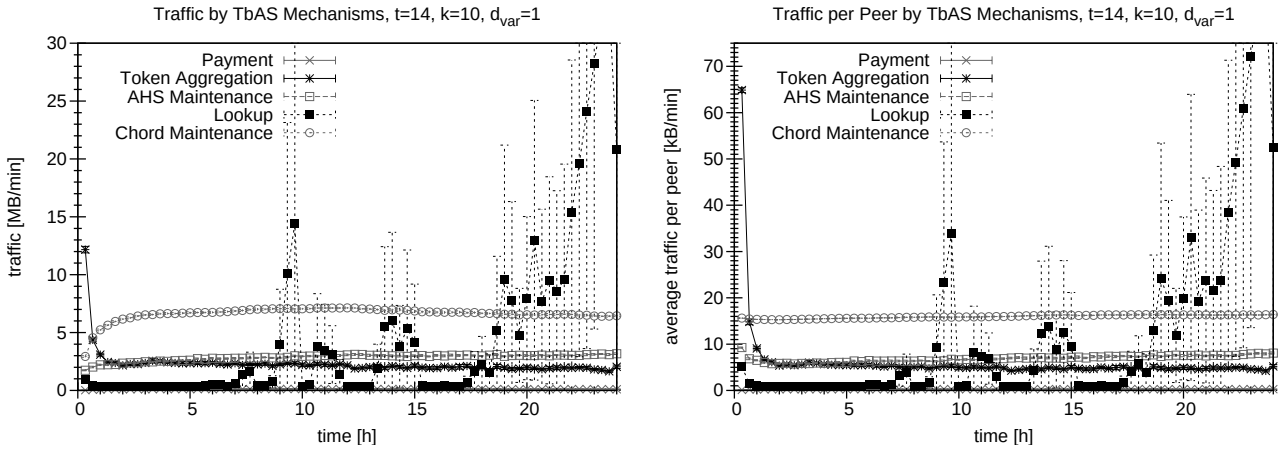
Figure E.11: System-wide token-based accounting traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 1$



(a) Traffic ratios including service traffic (b) Traffic ratios of token-based accounting

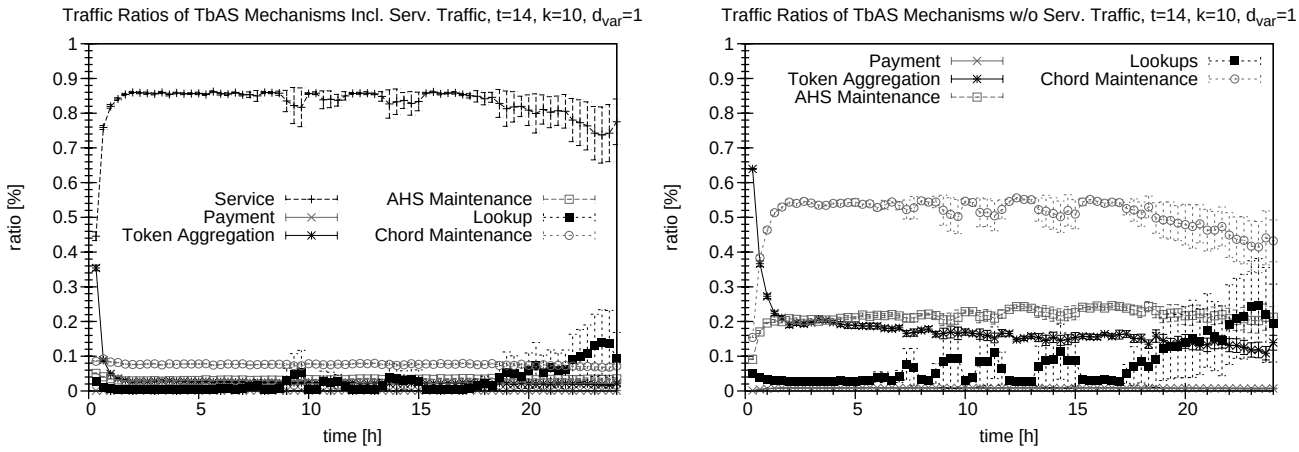
Figure E.12: System-wide traffic ratios for $t = 17$, $k = 10$, $d_{var} = 1$

Traffic Breakdown for $t = 14$, $k = 10$, $d_{var} = 1$



(a) System-wide traffic (b) Average traffic per active peer

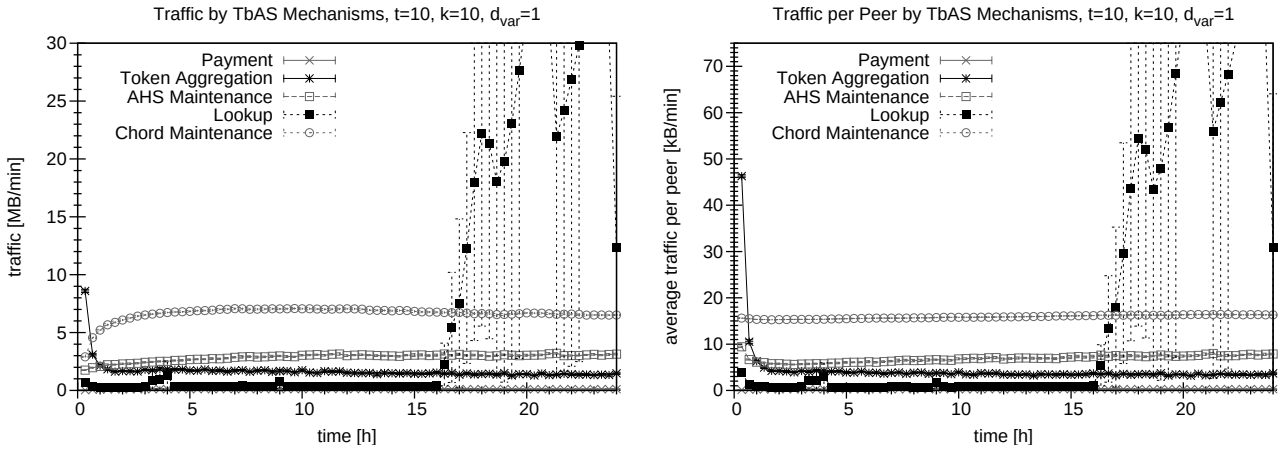
Figure E.13: System-wide token-based accounting traffic breakdown for $t = 14$, $k = 10$, $d_{var} = 1$



(a) Traffic ratios including service traffic (b) Traffic ratios of token-based accounting

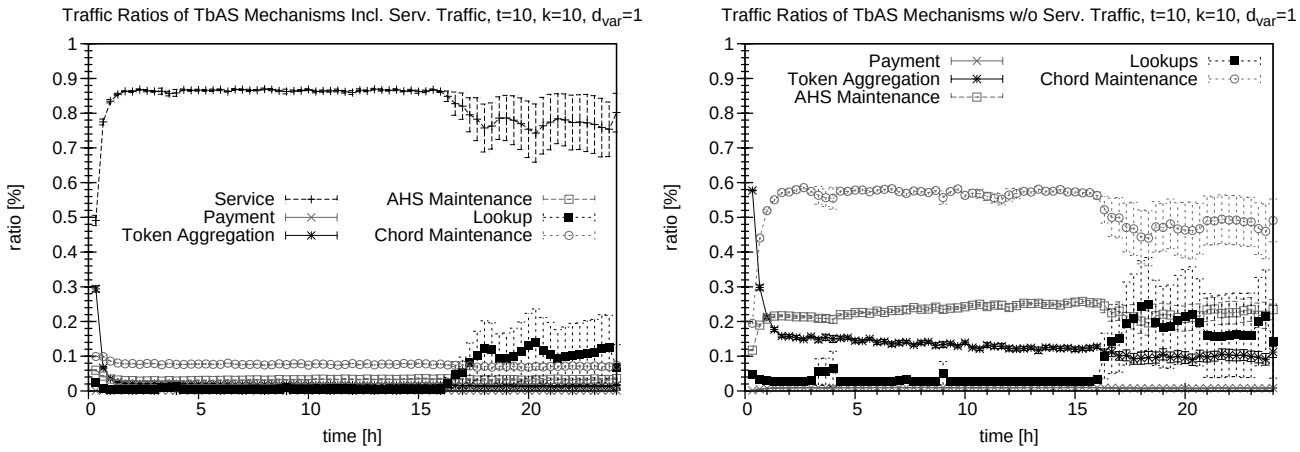
Figure E.14: System-wide traffic ratios for $t = 14$, $k = 10$, $d_{var} = 1$

Traffic Breakdown for $t = 10$, $k = 10$, $d_{var} = 1$



(a) System-wide traffic (b) Average traffic per active peer

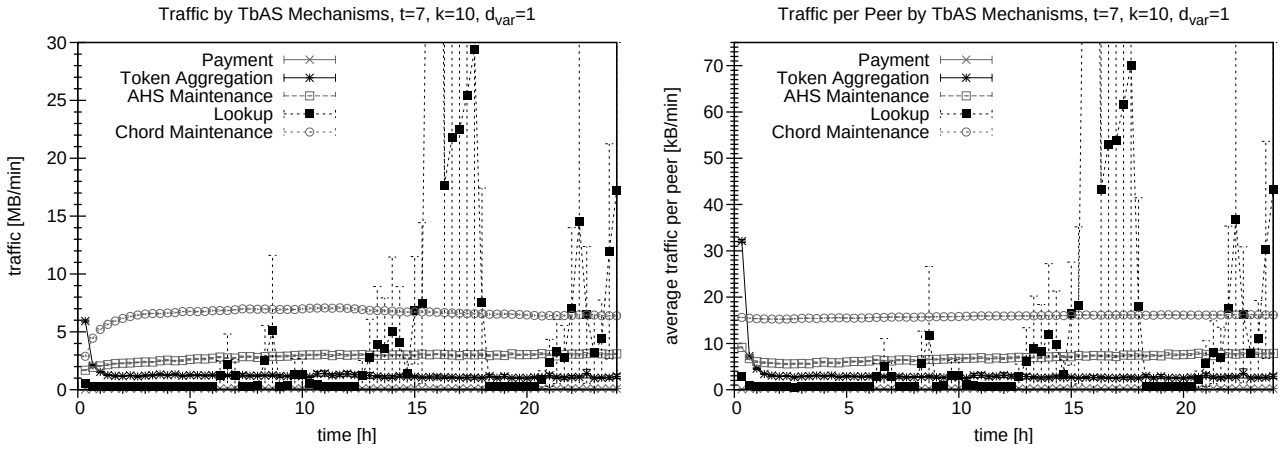
Figure E.15: System-wide token-based accounting traffic breakdown for $t = 10$, $k = 10$, $d_{var} = 1$



(a) Traffic ratios including service traffic (b) Traffic ratios of token-based accounting

Figure E.16: System-wide traffic ratios for $t = 10$, $k = 10$, $d_{var} = 1$

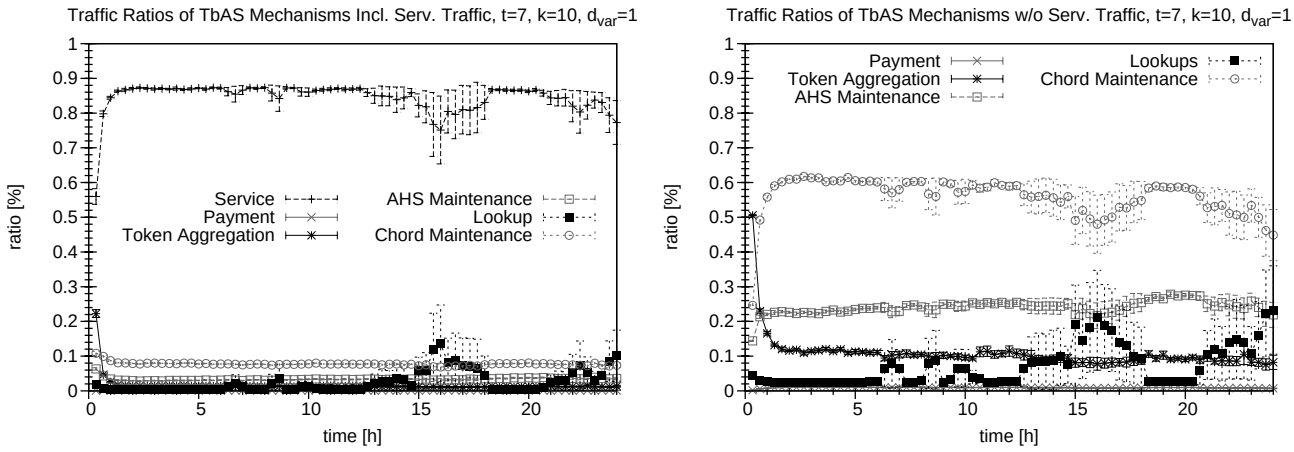
Traffic Breakdown for $t = 7$, $k = 10$, $d_{var} = 1$



(a) System-wide traffic

(b) Average traffic per active peer

Figure E.17: System-wide token-based accounting traffic breakdown for $t = 7$, $k = 10$, $d_{var} = 1$



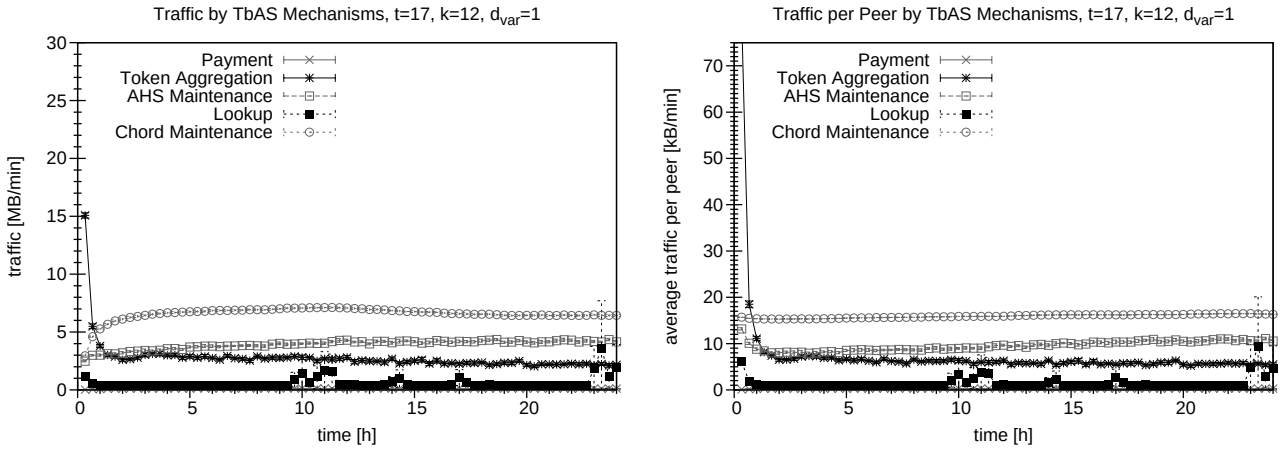
(a) Traffic ratios including service traffic

(b) Traffic ratios of token-based accounting

Figure E.18: System-wide traffic ratios for $t = 7$, $k = 10$, $d_{var} = 1$

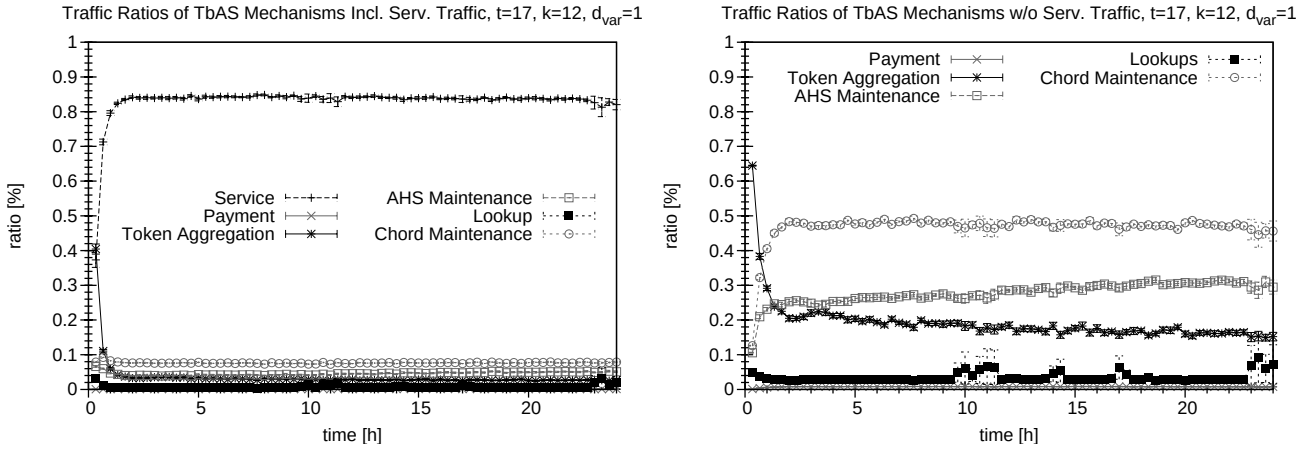
E.2.2.2 Traffic Breakdown by Account Holder Set Size

Traffic Breakdown for $t = 17$, $k = 12$, $d_{var} = 1$



(a) System-wide traffic (b) Average traffic per active peer

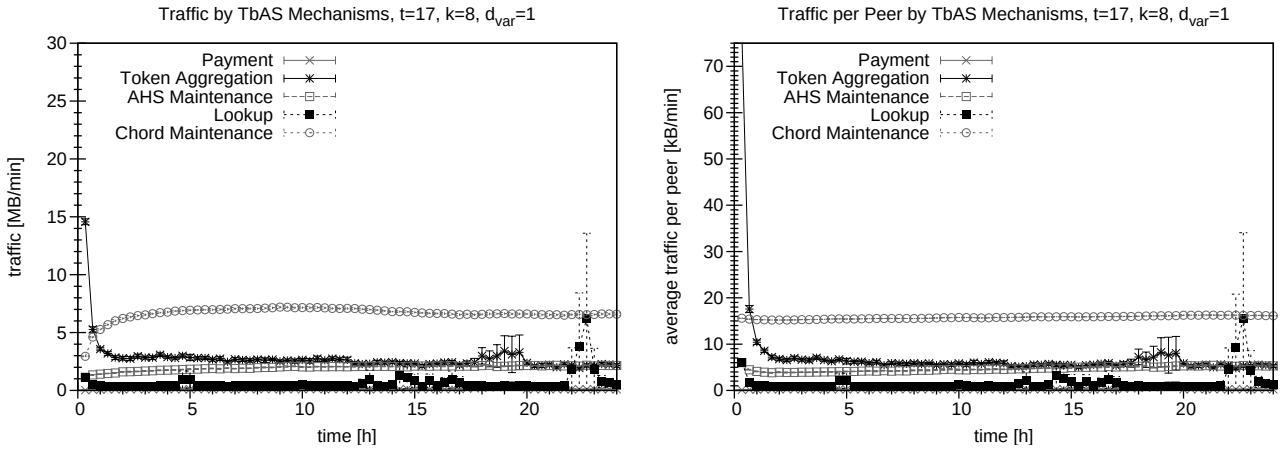
Figure E.19: System-wide token-based accounting traffic breakdown for $t = 17$, $k = 12$, $d_{var} = 1$



(a) Traffic ratios including service traffic (b) Traffic ratios of token-based accounting

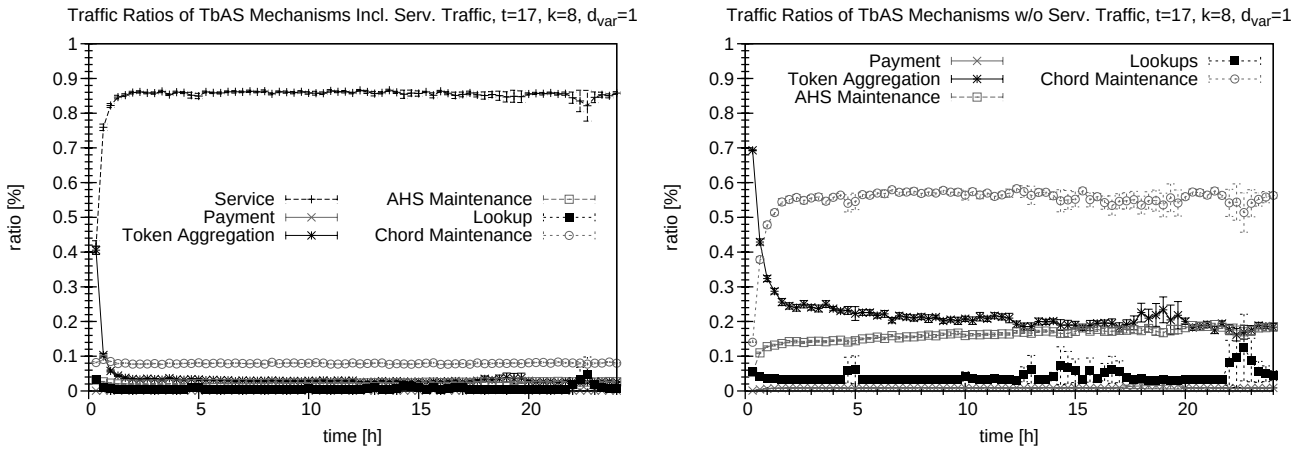
Figure E.20: System-wide traffic ratios for $t = 17$, $k = 12$, $d_{var} = 1$

Traffic Breakdown for $t = 17$, $k = 8$, $d_{var} = 1$



(a) System-wide traffic (b) Average traffic per active peer

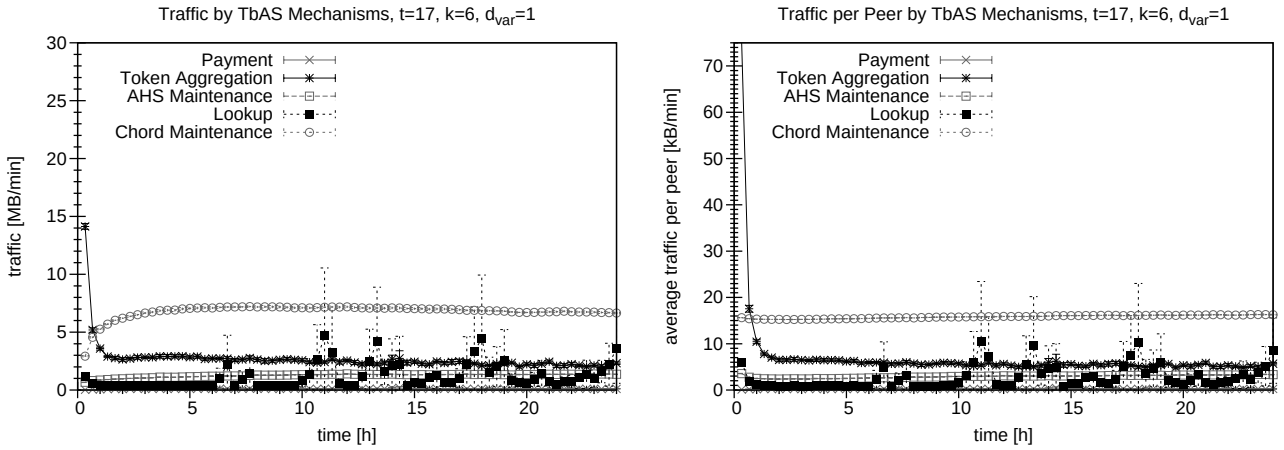
Figure E.21: System-wide token-based accounting traffic breakdown for $t = 17$, $k = 8$, $d_{var} = 1$



(a) Traffic ratios including service traffic (b) Traffic ratios of token-based accounting

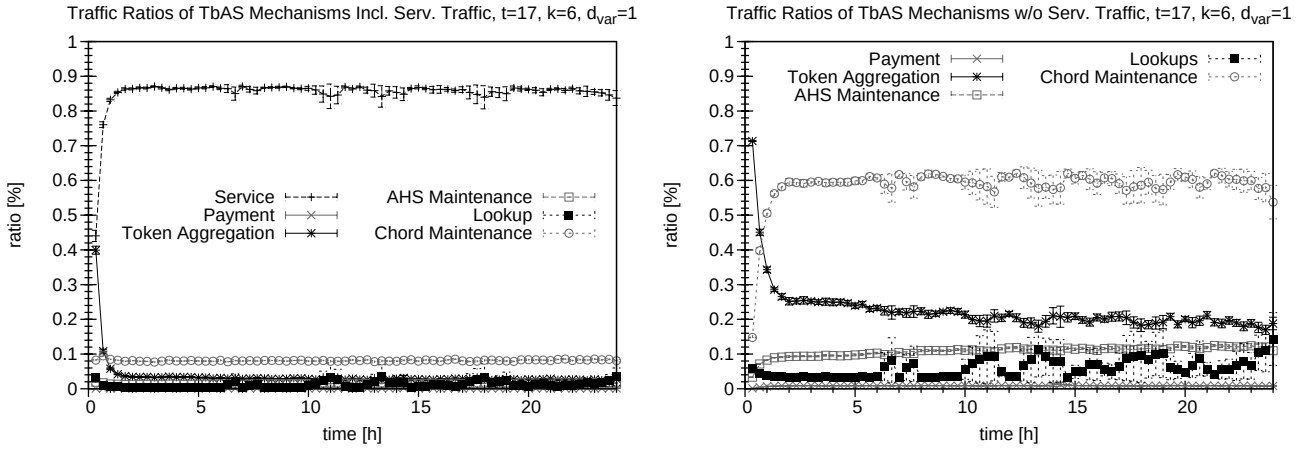
Figure E.22: System-wide traffic ratios for $t = 17$, $k = 8$, $d_{var} = 1$

Traffic Breakdown for $t = 17$, $k = 6$, $d_{var} = 1$



(a) System-wide traffic (b) Average traffic per active peer

Figure E.23: System-wide token-based accounting traffic breakdown for $t = 17$, $k = 6$, $d_{var} = 1$

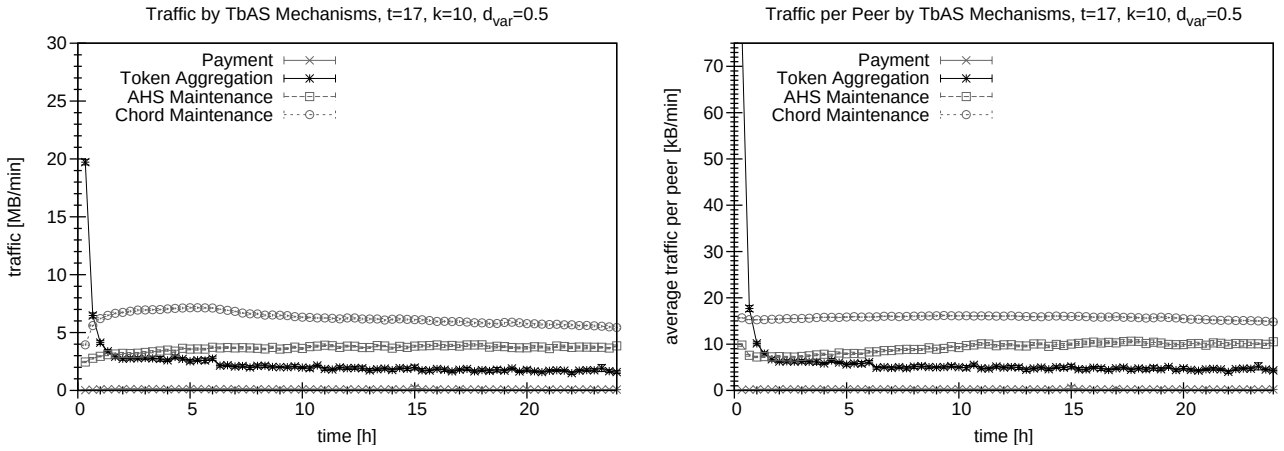


(a) Traffic ratios including service traffic (b) Traffic ratios of token-based accounting

Figure E.24: System-wide traffic ratios for $t = 17$, $k = 6$, $d_{var} = 1$

E.2.2.3 Traffic Breakdown by Churn Factor

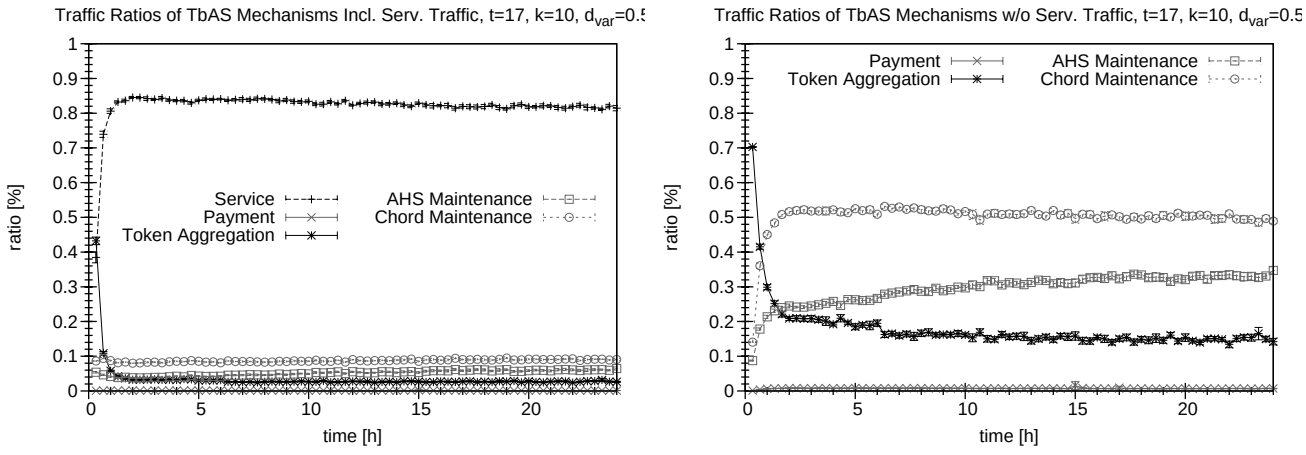
Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 0.5$ (Without Lookups)



(a) System-wide traffic

(b) Average traffic per active peer

Figure E.25: System-wide token-based accounting traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 0.5$

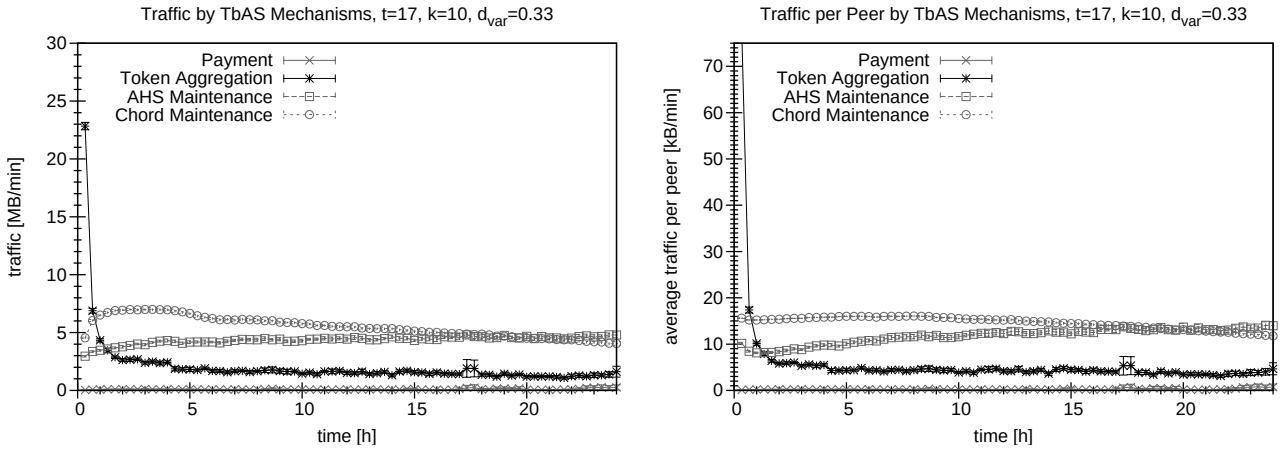


(a) Traffic ratios including service traffic

(b) Traffic ratios of token-based accounting

Figure E.26: System-wide traffic ratios for $t = 17$, $k = 10$, $d_{var} = 0.5$

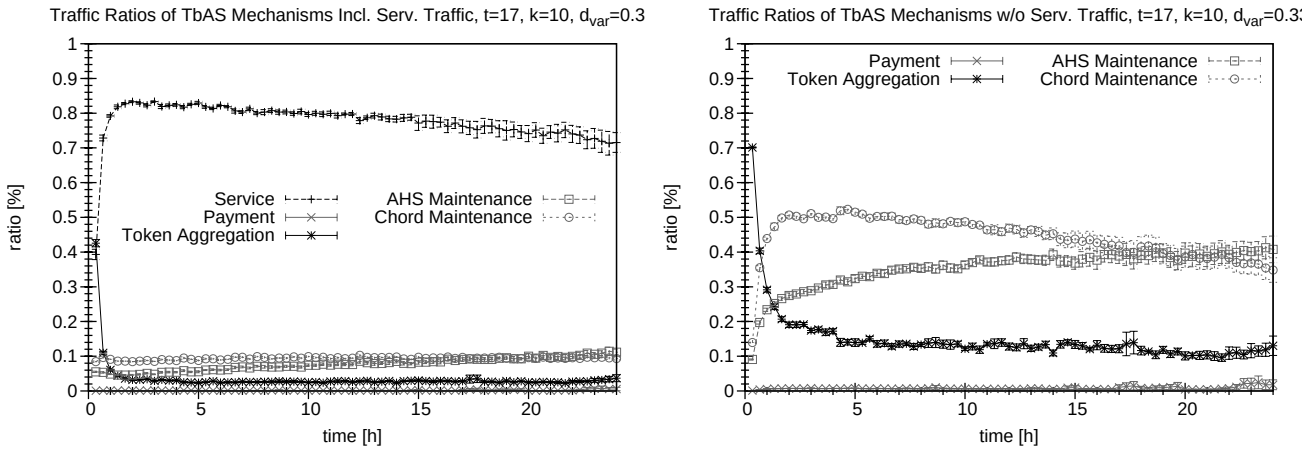
Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 0.33$ (Without Lookups)



(a) System-wide traffic

(b) Average traffic per active peer

Figure E.27: System-wide token-based accounting traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 0.33$

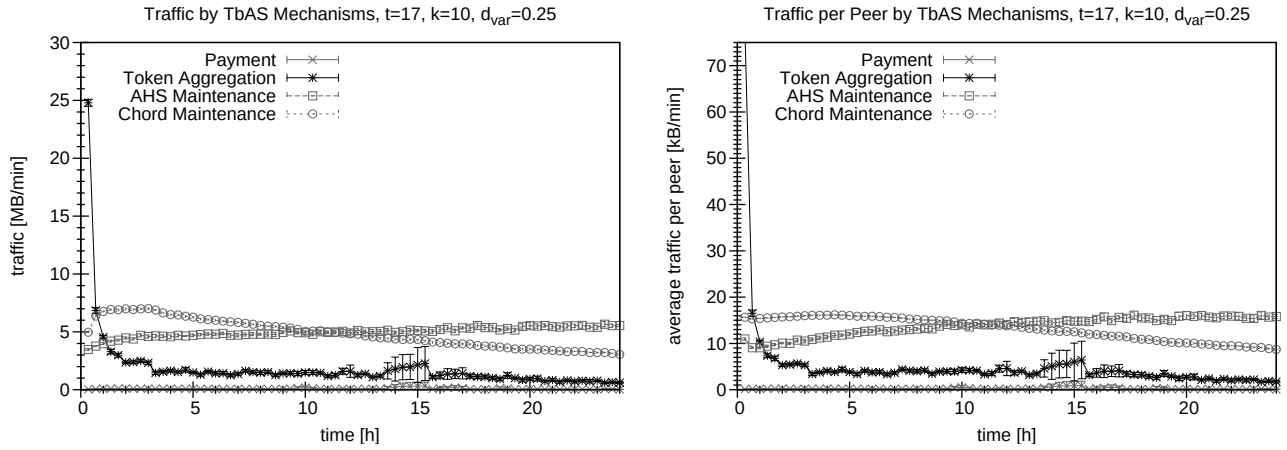


(a) Traffic ratios including service traffic

(b) Traffic ratios of token-based accounting

Figure E.28: System-wide traffic ratios for $t = 17$, $k = 10$, $d_{var} = 0.33$

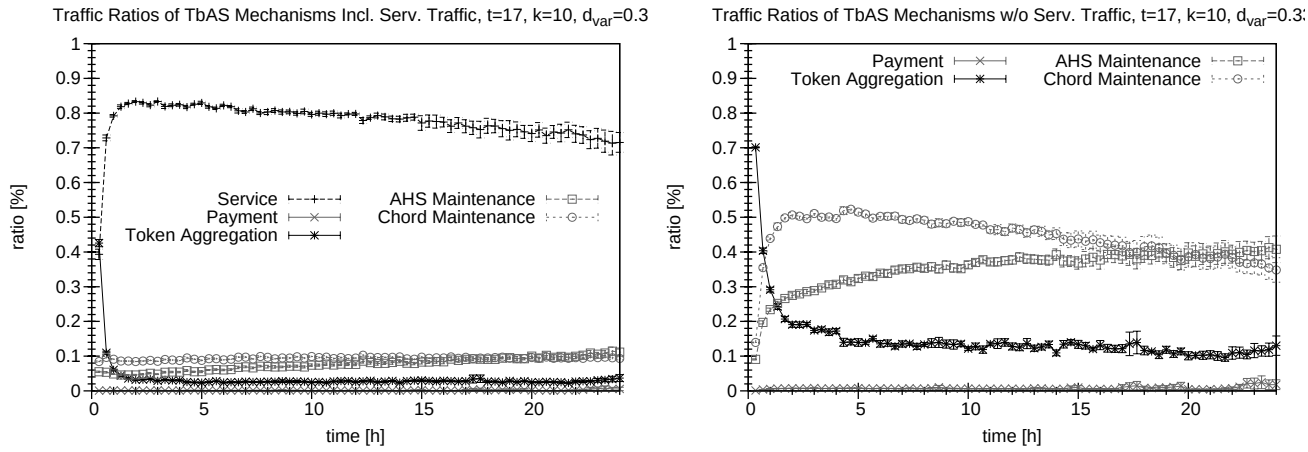
Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 0.25$ (Without Lookups)



(a) System-wide traffic

(b) Average traffic per active peer

Figure E.29: System-wide token-based accounting traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 0.25$



(a) Traffic ratios including service traffic

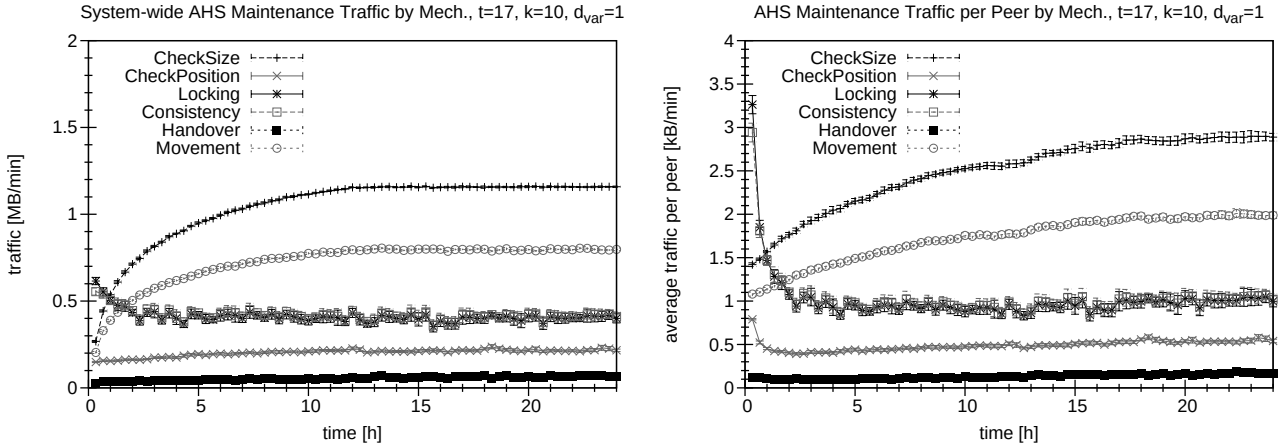
(b) Traffic ratios of token-based accounting

Figure E.30: System-wide traffic ratios for $t = 17$, $k = 10$, $d_{var} = 0.25$

E.2.3 Maintenance Traffic Breakdown

E.2.3.1 Maintenance Traffic Breakdown by Quorum Size

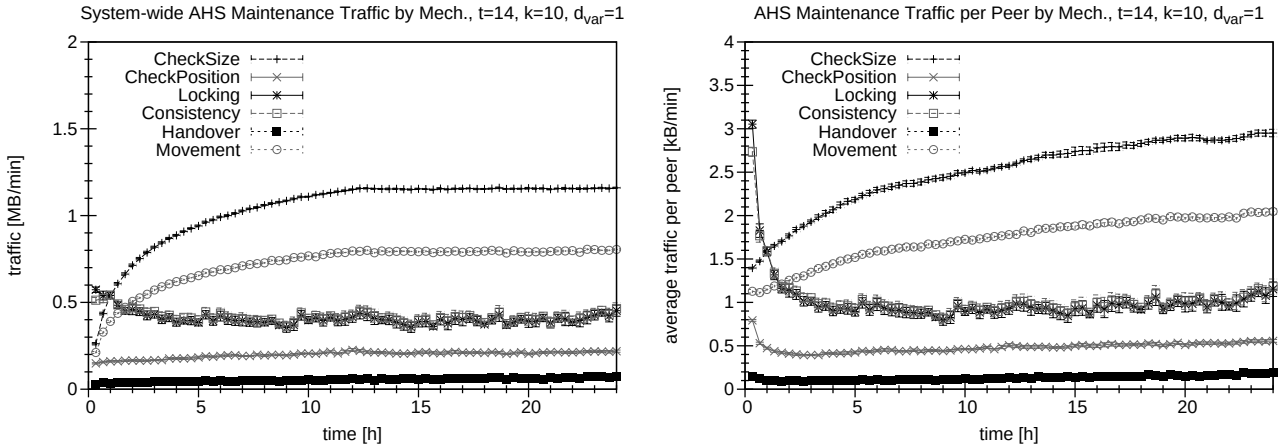
Maintenance Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 1$



(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.31: Maintenance traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 1$

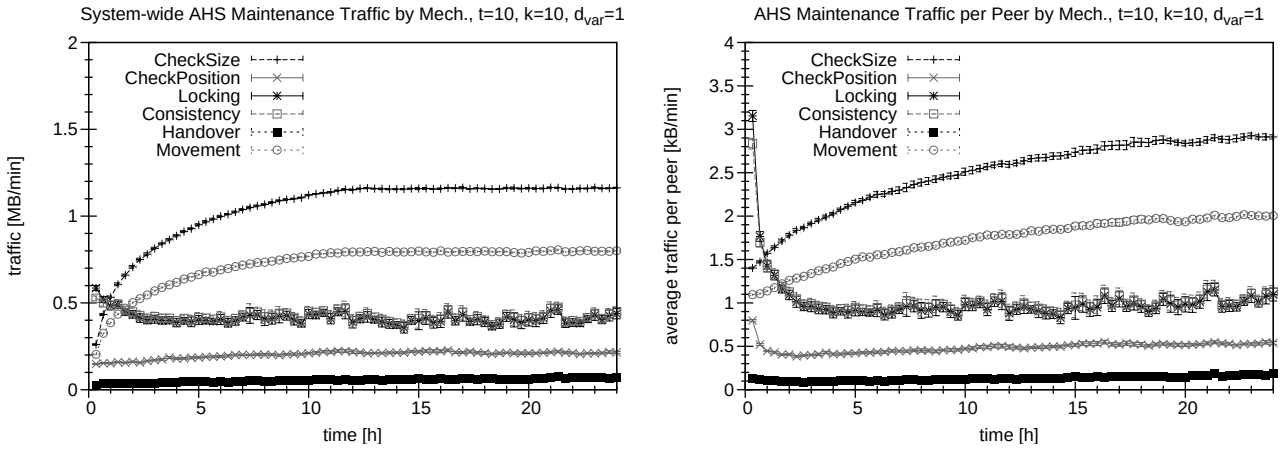
Maintenance Traffic Breakdown for $t = 14$, $k = 10$, $d_{var} = 1$



(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.32: Maintenance traffic breakdown for $t = 10$, $k = 10$, $d_{var} = 1$

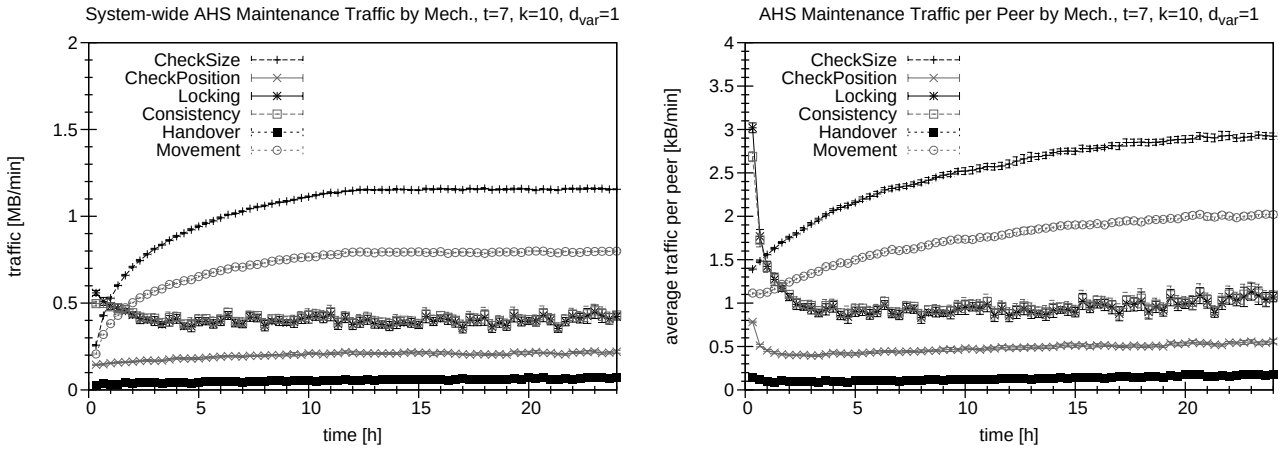
Maintenance Traffic Breakdown for $t = 10$, $k = 10$, $d_{var} = 1$



(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.33: Maintenance traffic breakdown for $t = 7$, $k = 10$, $d_{var} = 1$

Maintenance Traffic Breakdown for $t = 7$, $k = 10$, $d_{var} = 1$

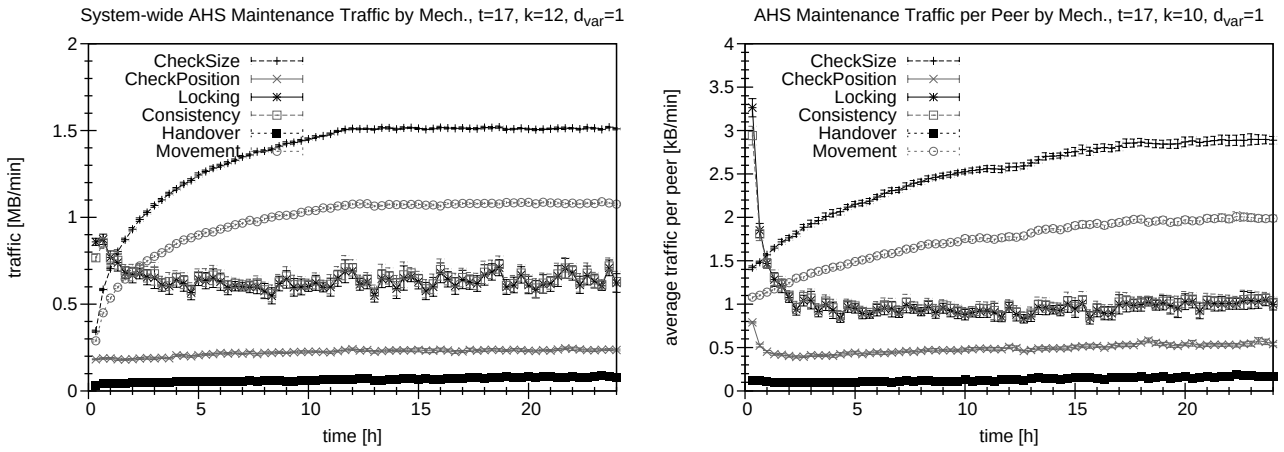


(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.34: Maintenance traffic breakdown for $t = 7$, $k = 10$, $d_{var} = 1$

E.2.3.2 Maintenance Traffic Breakdown by Account Holder Set Size

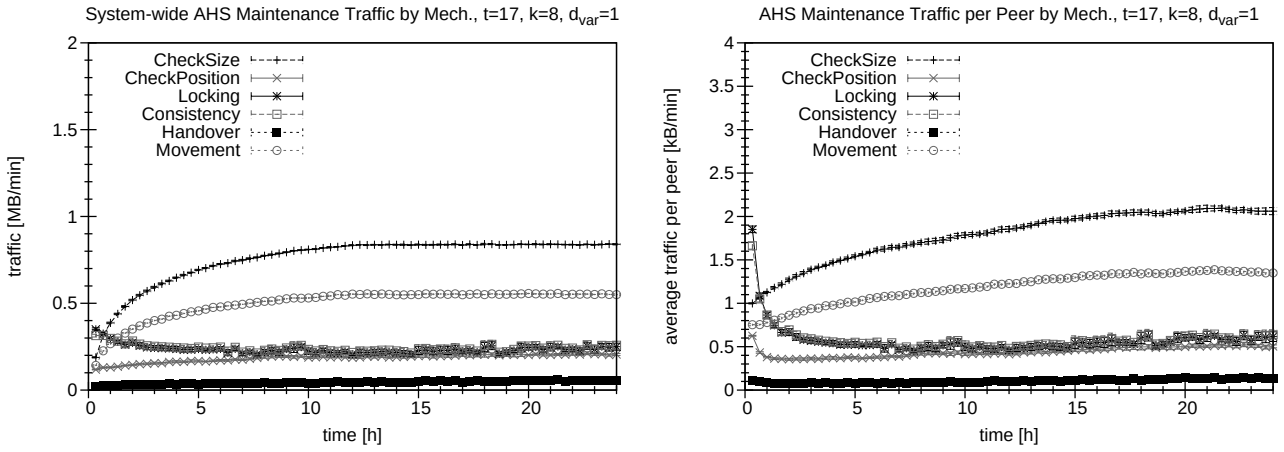
Maintenance Traffic Breakdown for $t = 17$, $k = 12$, $d_{var} = 1$



(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.35: Maintenance traffic breakdown for $t = 17$, $k = 12$, $d_{var} = 1$

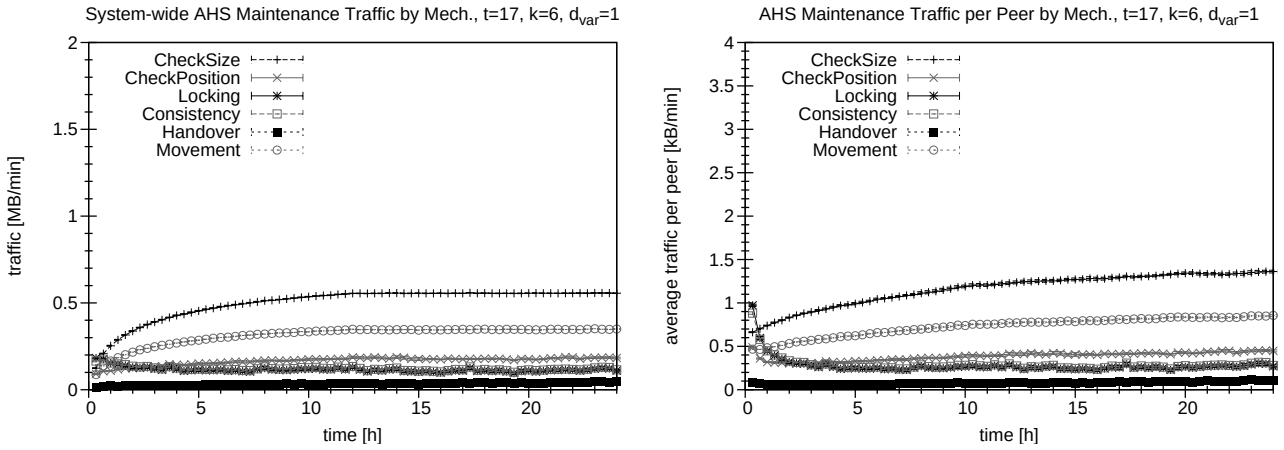
Maintenance Traffic Breakdown for $t = 17$, $k = 8$, $d_{var} = 1$



(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.36: Maintenance traffic breakdown for $t = 17$, $k = 8$, $d_{var} = 1$

Maintenance Traffic Breakdown for $t = 17$, $k = 6$, $d_{var} = 1$

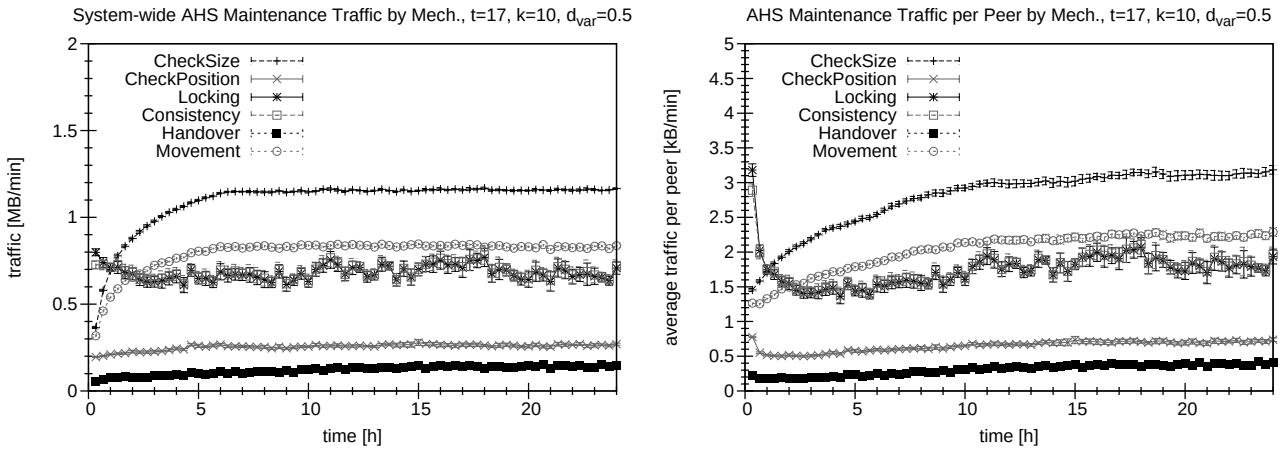


(a) Maintenance traffic breakdown

Figure E.37: Maintenance traffic breakdown for $t = 17$, $k = 6$, $d_{var} = 1$

E.2.3.3 Maintenance Traffic Breakdown by Churn Factor

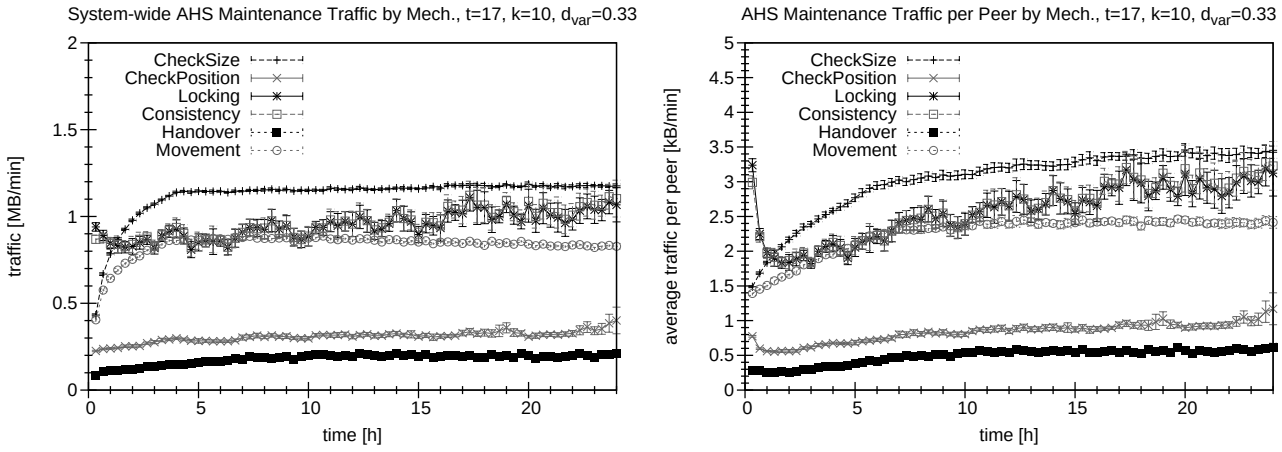
Maintenance Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 0.5$



(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.38: Maintenance traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 0.5$

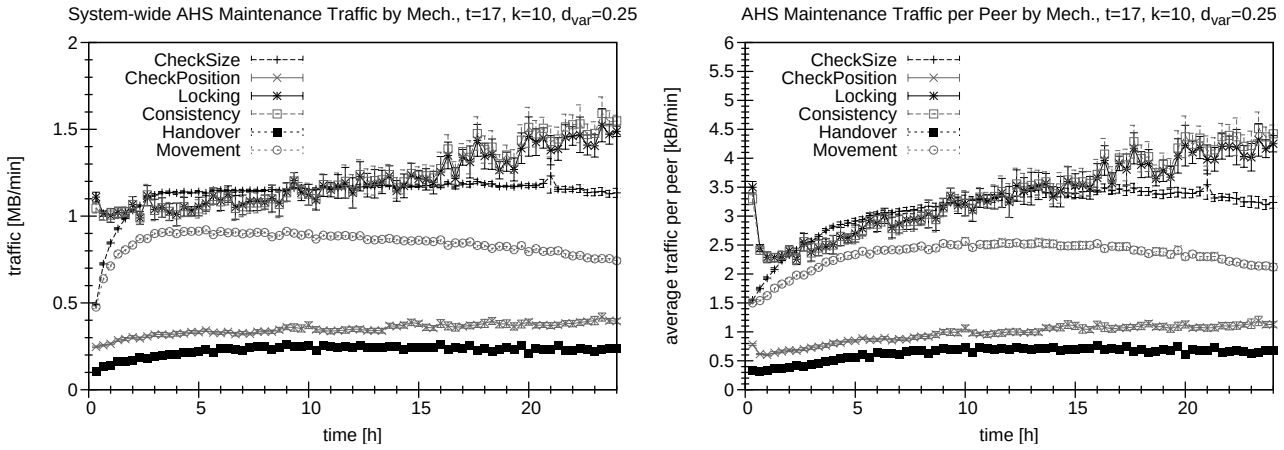
Maintenance Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 0.33$



(a) Maintenance traffic breakdown (b) Per peer maintenance traffic breakdown

Figure E.39: Maintenance traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 0.33$

Maintenance Traffic Breakdown for $t = 17$, $k = 10$, $d_{var} = 0.25$



(a) Maintenance traffic breakdown

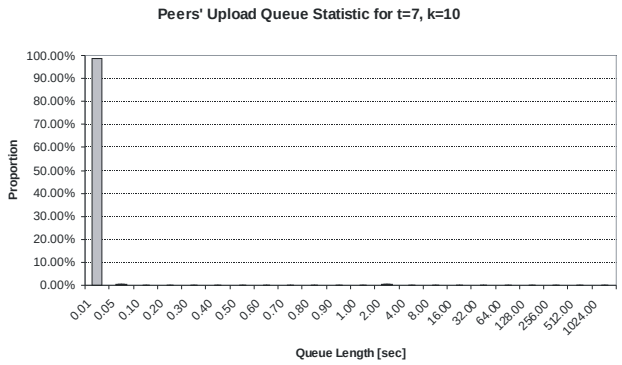
(b) Per peer maintenance traffic breakdown

Figure E.40: Maintenance traffic breakdown for $t = 17$, $k = 10$, $d_{var} = 0.25$

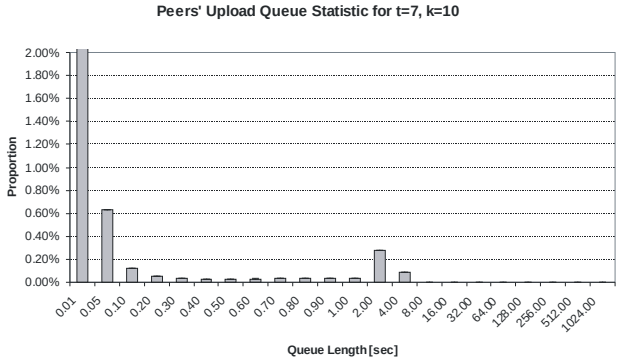
E.2.4 Peers' Upload Queue Length

E.2.4.1 Peers' Upload Queue Length by Quorum Size

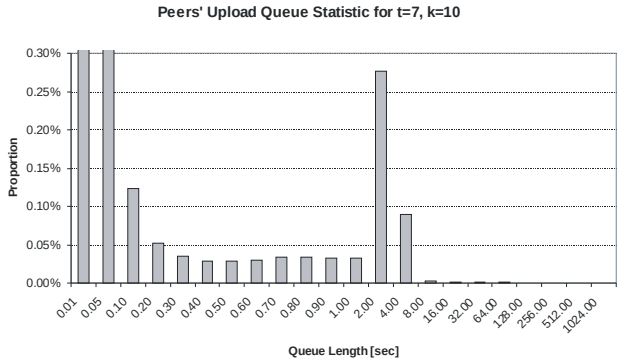
Peers' Upload Queue Length for $t = 7$, $k = 10$, $d_{var} = 1$



(a) Proportions of upload queue lengths, unfocused

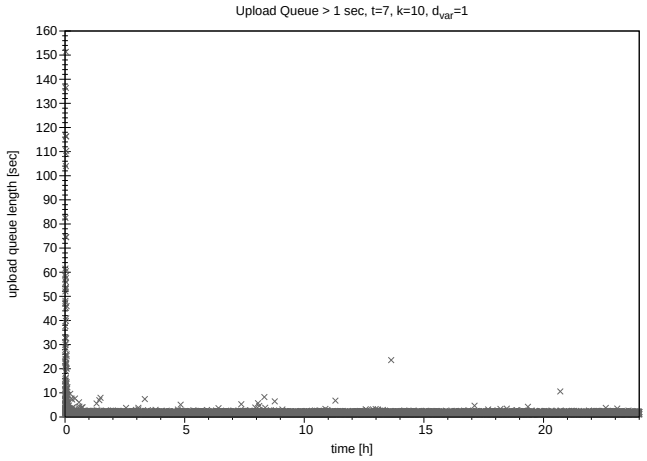


(b) Proportions of upload queue lengths, focused to lower 2%

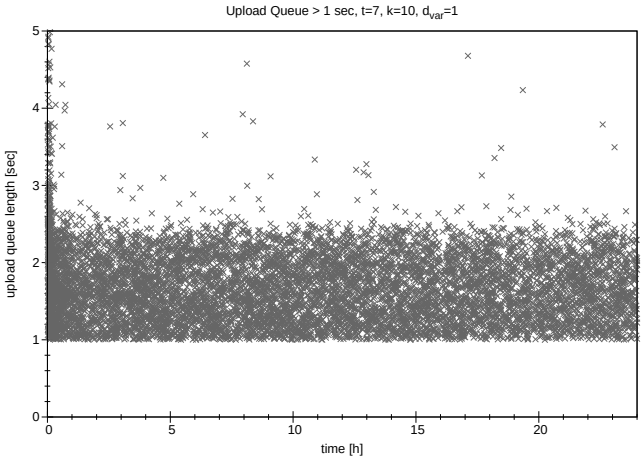


(c) Proportions of upload queue lengths, focused to lower 0.3%

Figure E.41: Peers' upload queue length distribution for $t = 7$, $k = 10$, $d_{var} = 1$



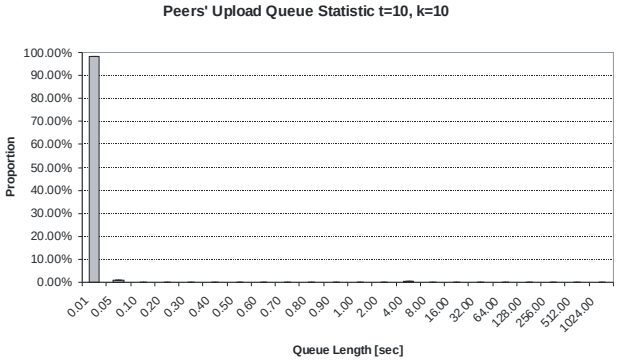
(a) Upload queue length by time

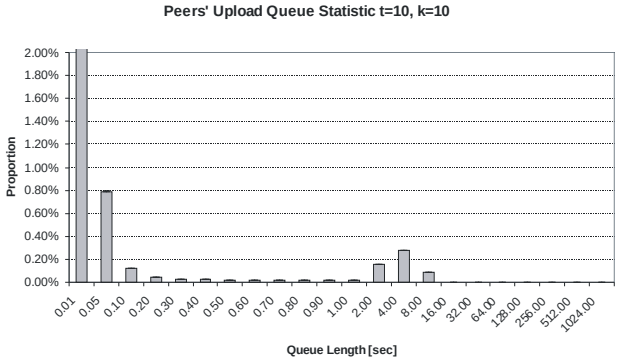


(b) Upload queue length by time, focused

Figure E.42: High peer loads by simulation time for $t = 7$, $k = 10$, $d_{var} = 1$

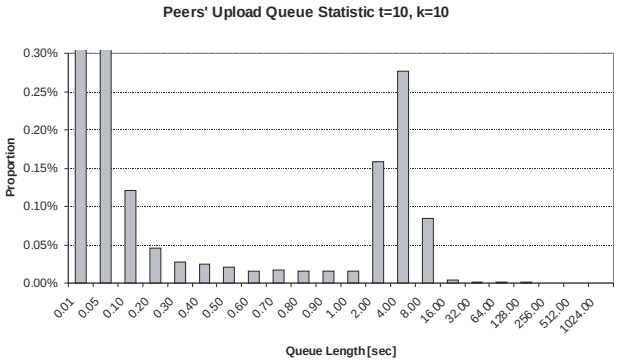
Peers' Upload Queue Length for $t = 10$, $k = 10$, $d_{var} = 1$





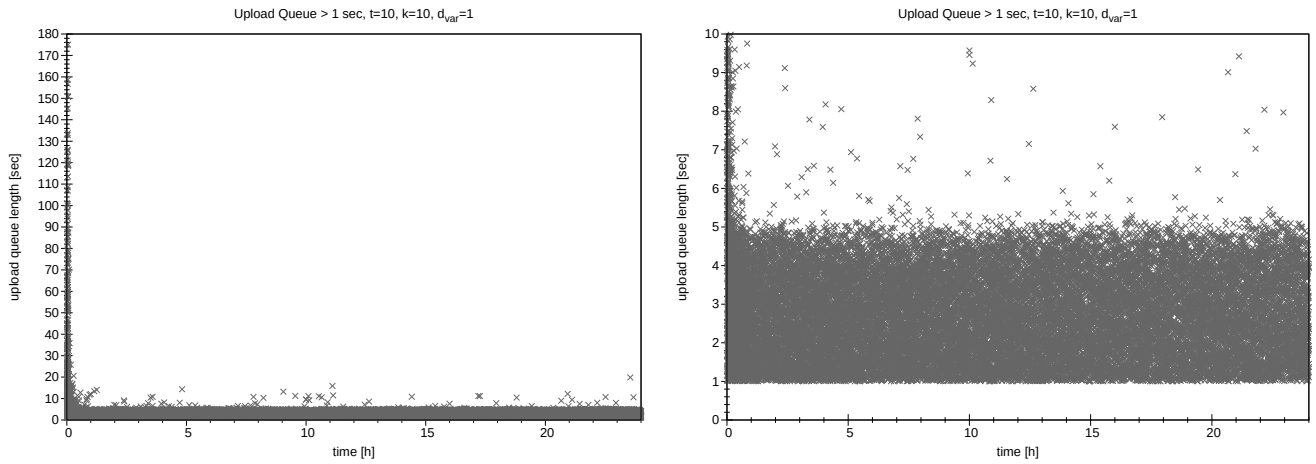
(a) Proportions of upload queue lengths, unfocused

(b) Proportions of upload queue lengths, focused to lower 2%



(c) Proportions of upload queue lengths, focused to lower 0.3%

Figure E.43: Peers' upload queue length distribution for $t = 10$, $k = 10$, $d_{var} = 1$

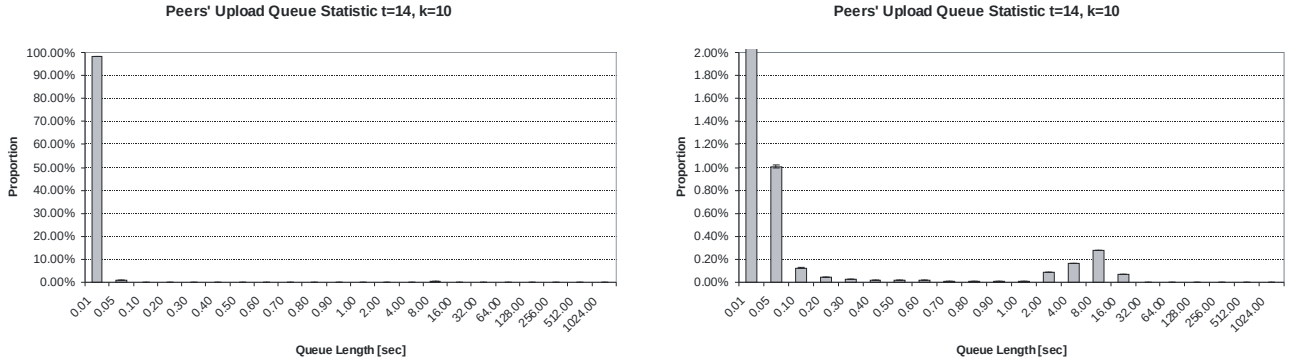


(a) Upload queue length by time

(b) Upload queue length by time, focused

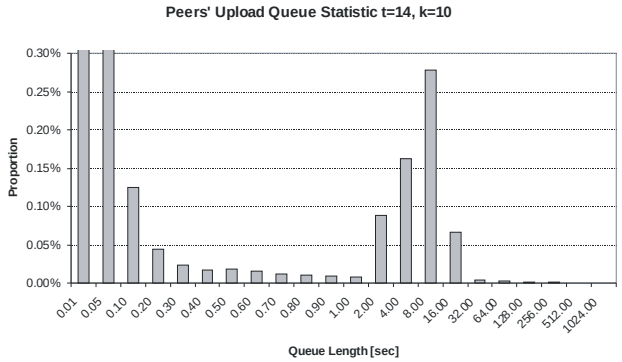
Figure E.44: High peer loads by simulation time for $t = 10$, $k = 10$, $d_{var} = 1$

Peers' Upload Queue Length for $t = 14$, $k = 10$, $d_{var} = 1$



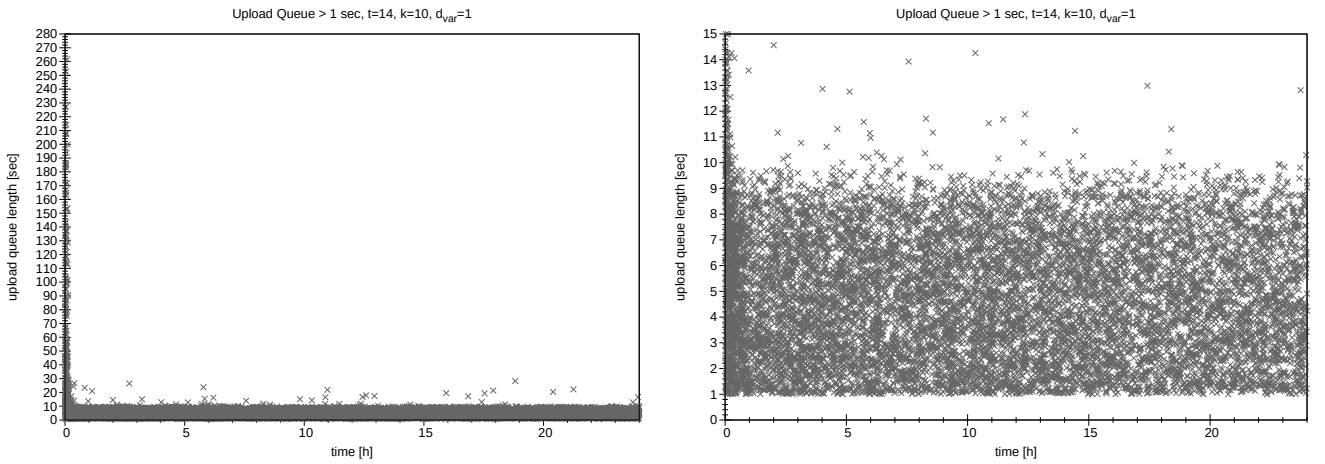
(a) Proportions of upload queue lengths, unfocused

(b) Proportions of upload queue lengths, focused to lower 2%



(c) Proportions of upload queue lengths, focused to lower 0.3%

Figure E.45: Peers' upload queue length distribution for $t = 14$, $k = 10$, $d_{var} = 1$

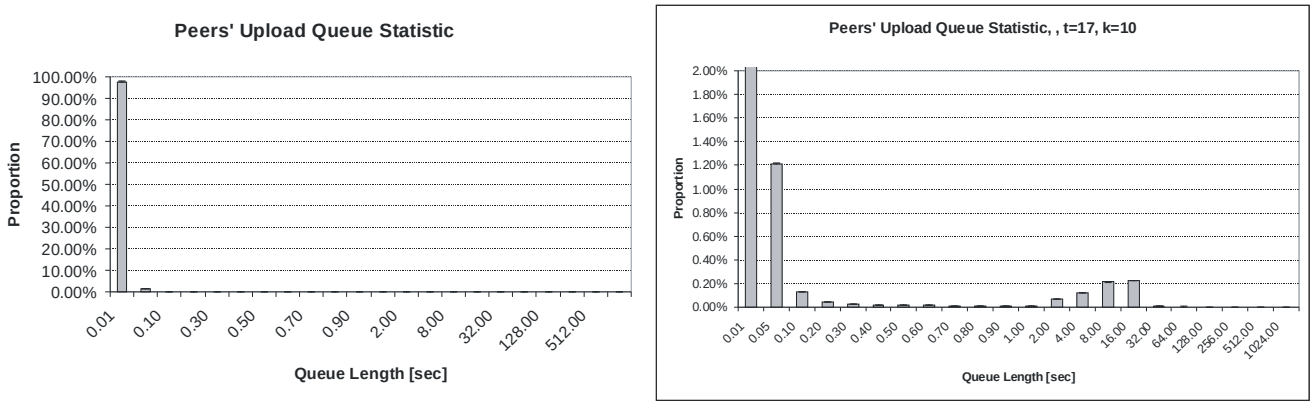


(a) Upload queue length by time

(b) Upload queue length by time, focused

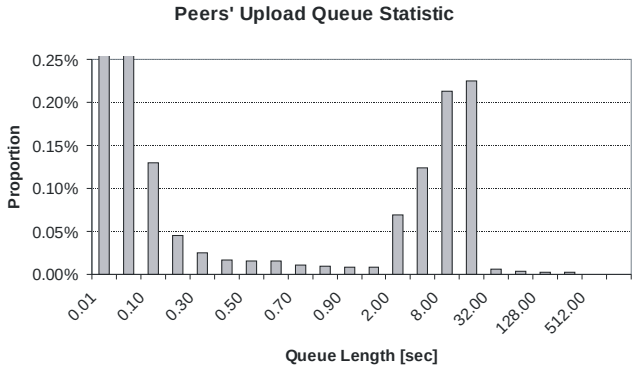
Figure E.46: High peer loads by simulation time for $t = 14$, $k = 10$, $d_{var} = 1$

Peers' Upload Queue Length for $t = 17$, $k = 10$, $d_{var} = 1$



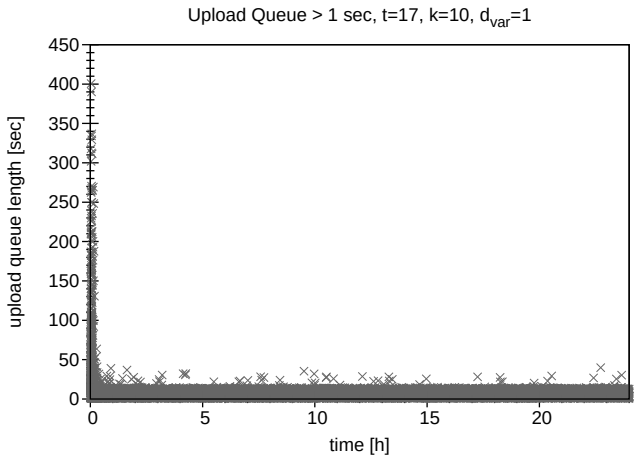
(a) Proportions of upload queue lengths, unfocused

(b) Proportions of upload queue lengths, focused to lower 2%

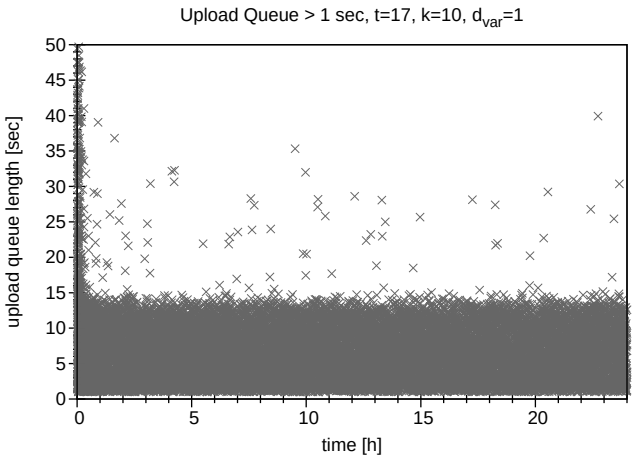


(c) Proportions of upload queue lengths, focused to lower 0.25%

Figure E.47: Peers' upload queue length distribution for $t = 17$, $k = 10$, $d_{var} = 1$



(a) Upload queue length by time

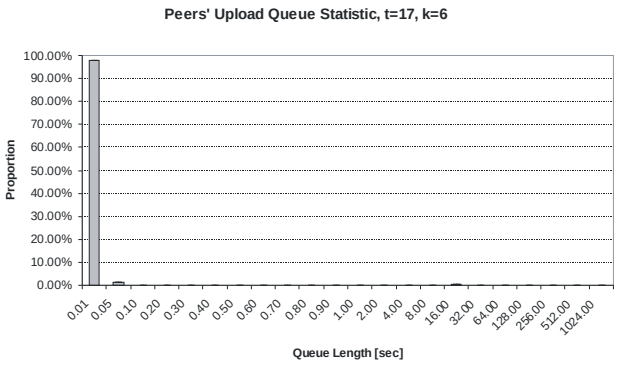


(b) Upload queue length by time, focused

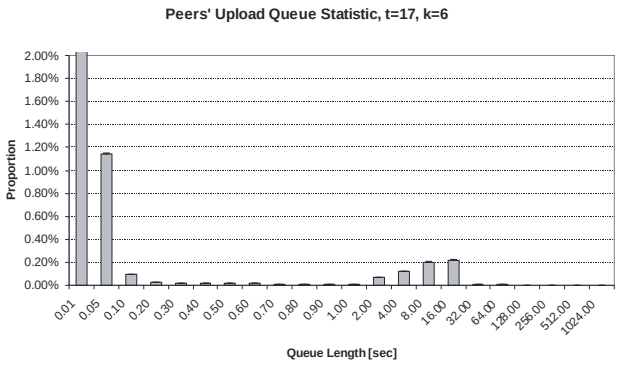
Figure E.48: High peer loads by simulation time for $t = 17$, $k = 10$, $d_{var} = 1$

E.2.4.2 Peers' Upload Queue Length by Account Holder Set Size

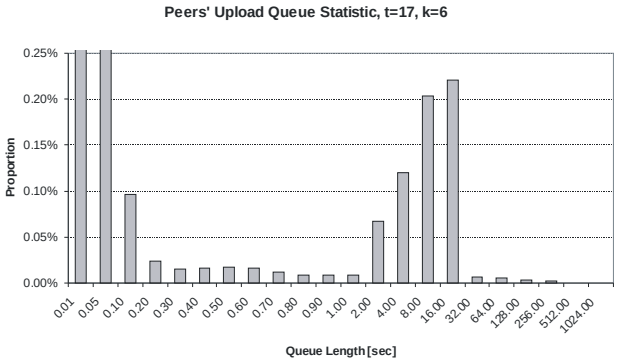
Peers' Upload Queue Length for $t = 17$, $k = 6$, $d_{var} = 1$



(a) Proportions of upload queue lengths, unfocused

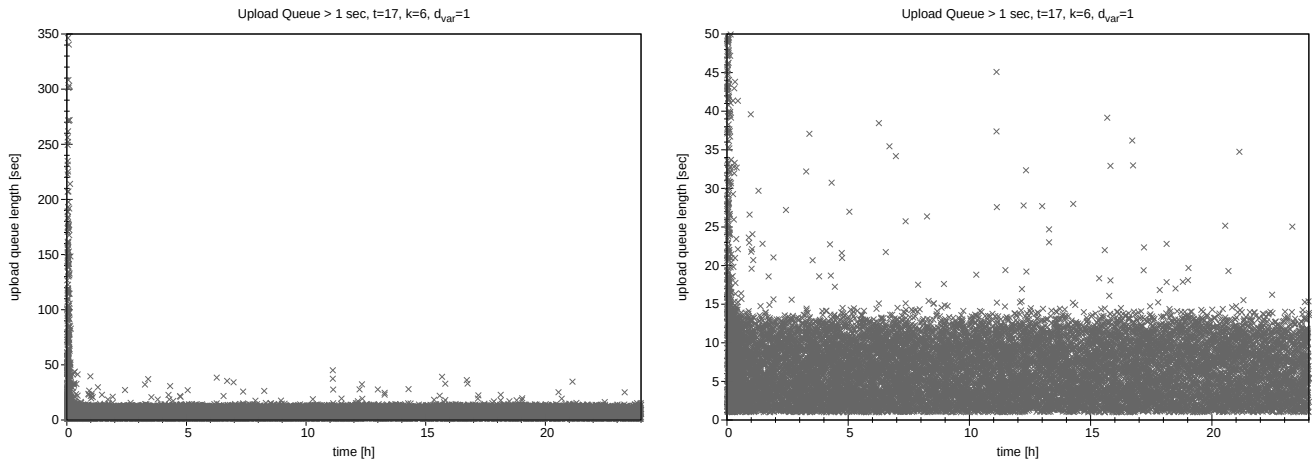


(b) Proportions of upload queue lengths, focused to lower 2%



(c) Proportions of upload queue lengths, focused to lower 0.3%

Figure E.49: Peers' upload queue length distribution for $t = 17$, $k = 6$, $d_{var} = 1$

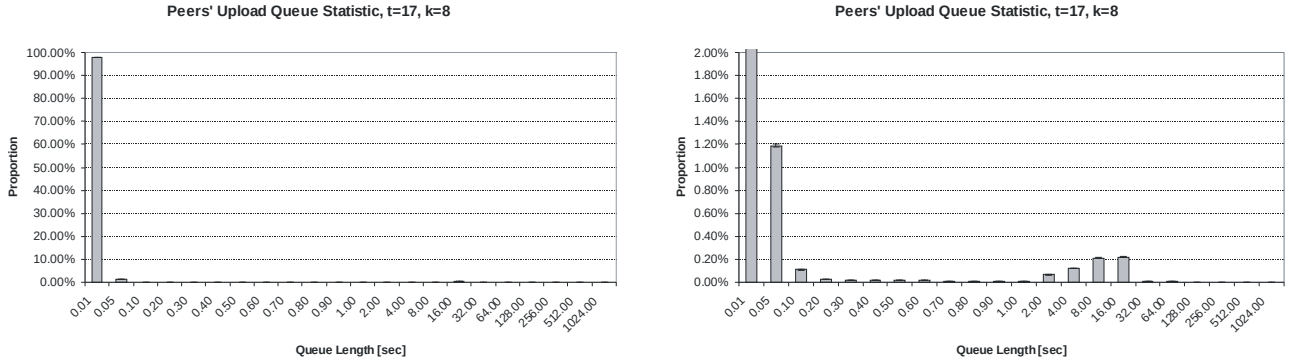


(a) Upload queue length by time

(b) Upload queue length by time, focused

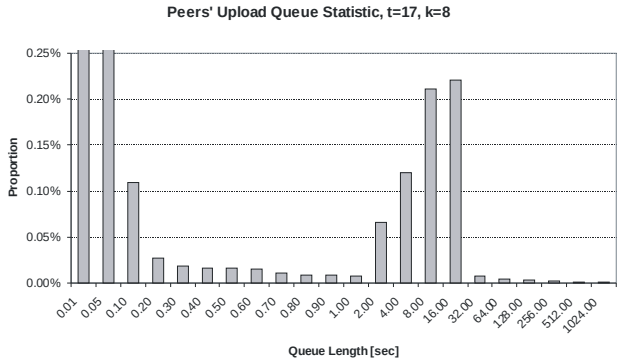
Figure E.50: High peer loads by simulation time for $t = 17$, $k = 6$, $d_{var} = 1$

Peers' Upload Queue Length for $t = 17$, $k = 8$, $d_{var} = 1$



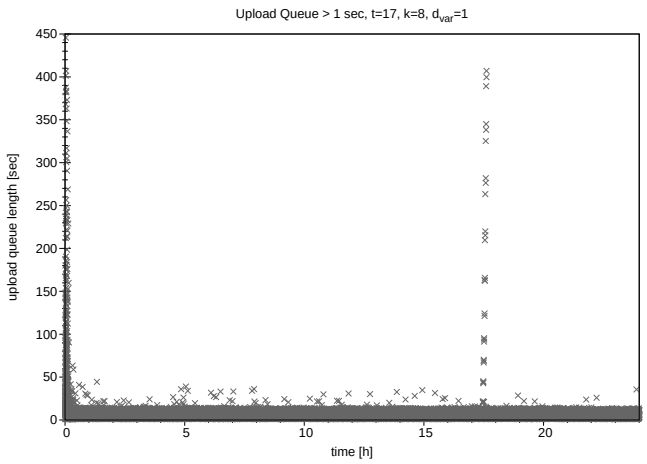
(a) Proportions of upload queue lengths, unfocused

(b) Proportions of upload queue lengths, focused to lower 2%

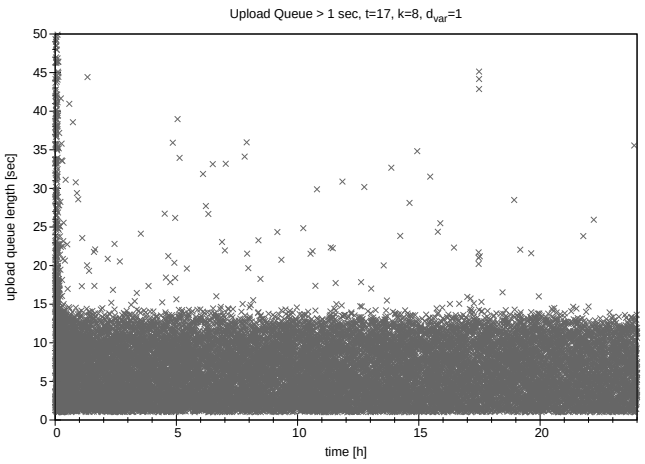


(c) Proportions of upload queue lengths, focused to lower 0.3%

Figure E.51: Peers' upload queue length distribution for $t = 17$, $k = 8$, $d_{var} = 1$



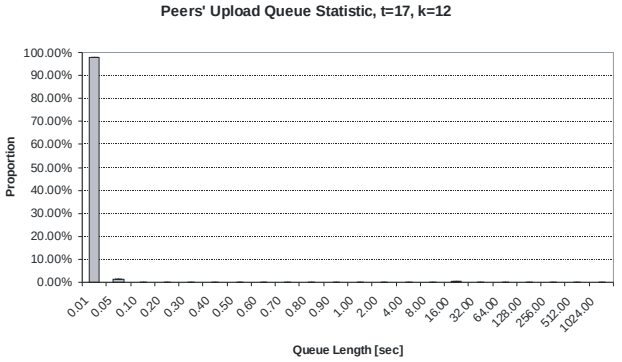
(a) Upload queue length by time

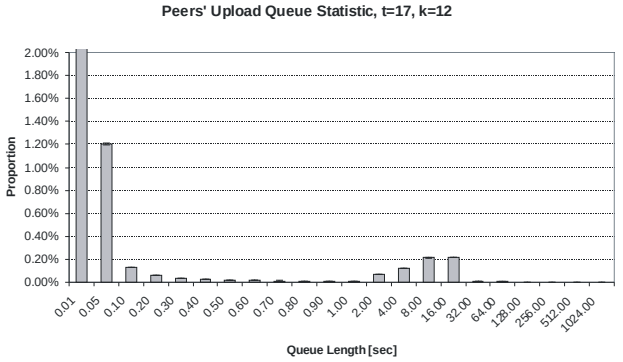


(b) Upload queue length by time, focused

Figure E.52: High peer loads by simulation time for $t = 17$, $k = 8$, $d_{var} = 1$

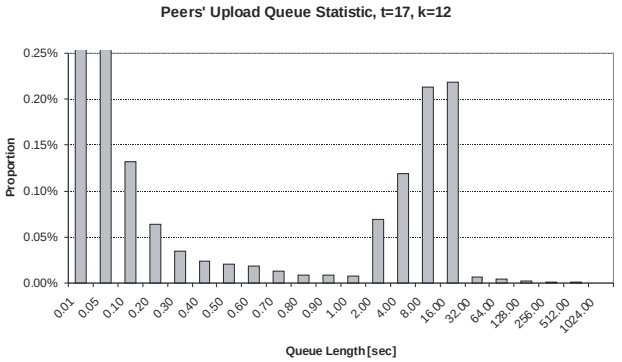
Peers' Upload Queue Length for $t = 17$, $k = 12$, $d_{var} = 1$





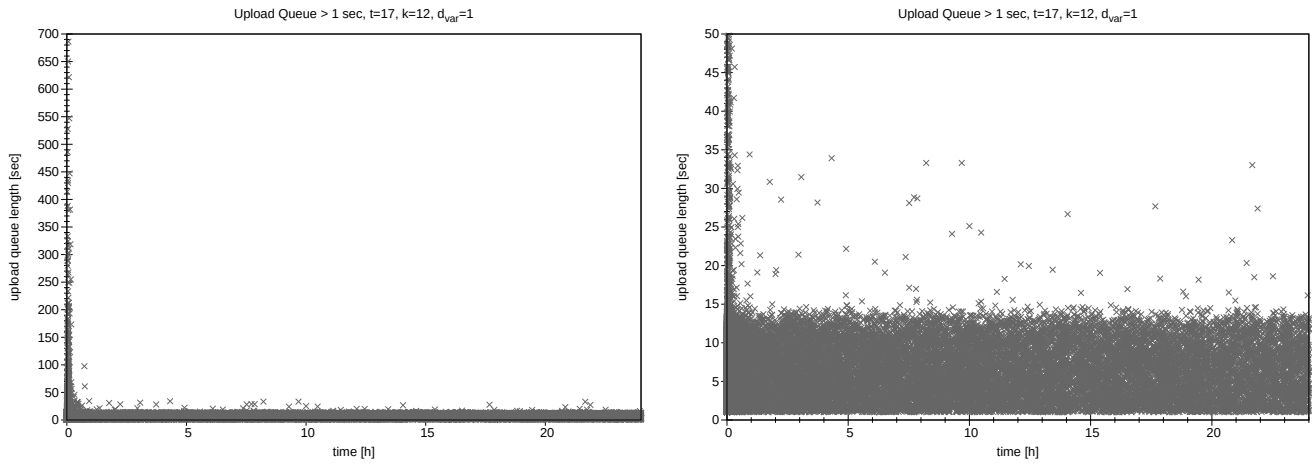
(a) Proportions of upload queue lengths, unfocused

(b) Proportions of upload queue lengths, focused to lower 2%



(c) Proportions of upload queue lengths, focused to lower 0.25%

Figure E.53: Peers' upload queue length distribution for $t = 17$, $k = 12$, $d_{var} = 1$



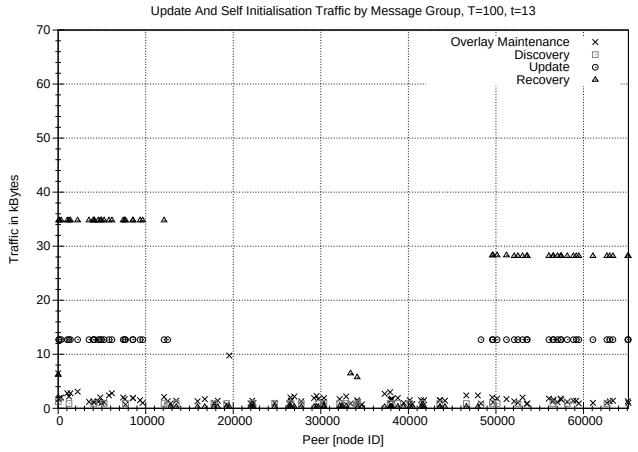
(a) Upload queue length by time

(b) Upload queue length by time, focused

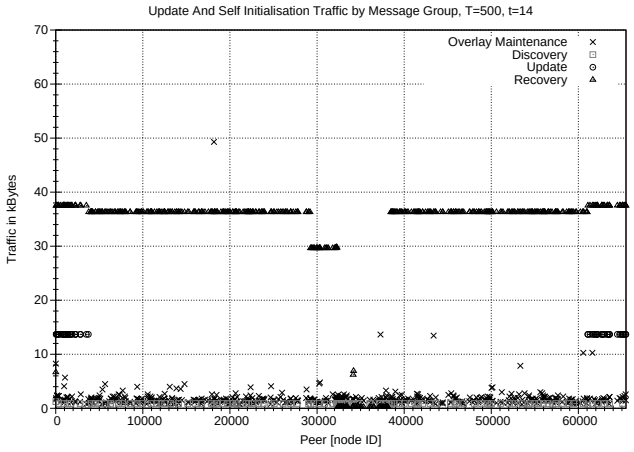
Figure E.54: High peer loads by simulation time for $t = 17$, $k = 12$, $d_{var} = 1$

E.3 Simulation of Key Management Traffic

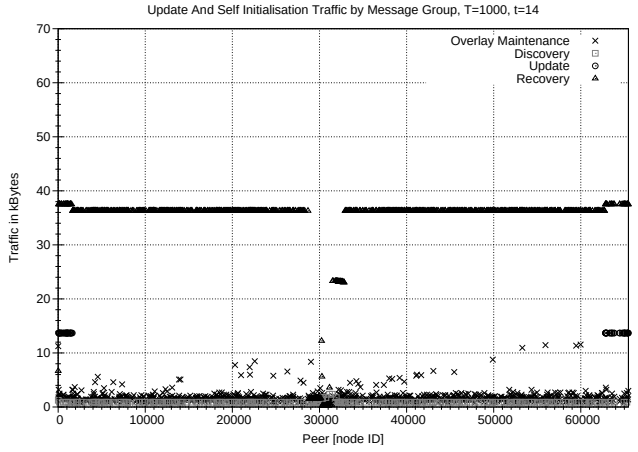
E.3.1 Update And Self Initialisation Traffic by Message Group



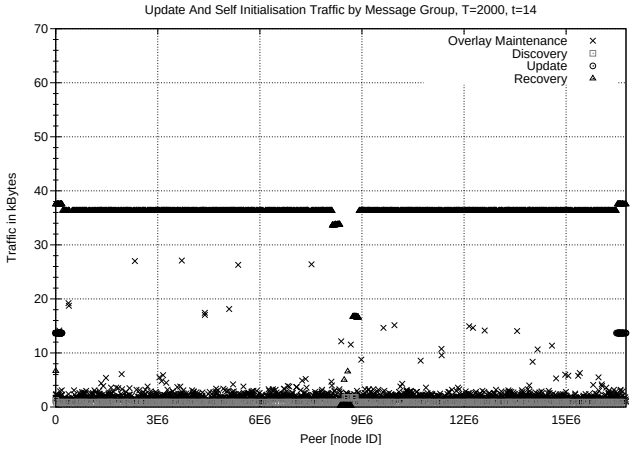
(a) Traffic by message group, T=100, t=13



(b) Traffic by message group, T=500, t=14

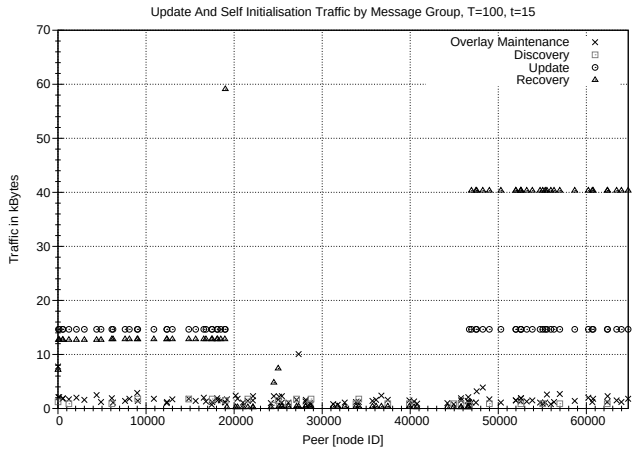


(c) Traffic by message group, T=1000, t=14

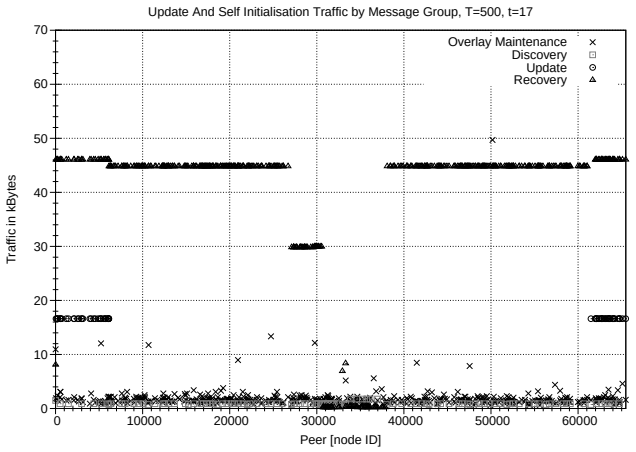


(d) Traffic by message group, T=2000, t=14

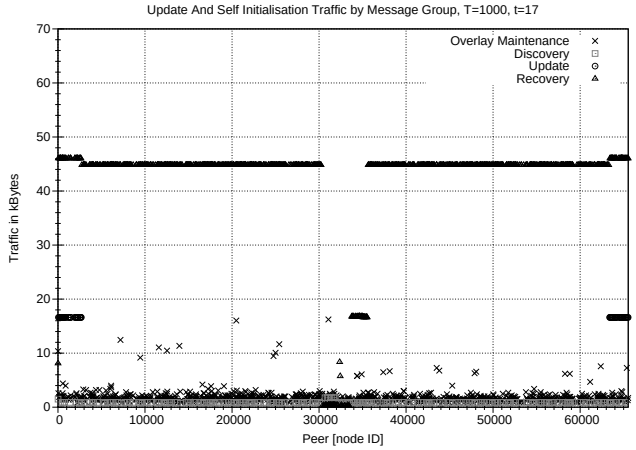
Figure E.55: Simulation results for $L_1 = 99,99\%$



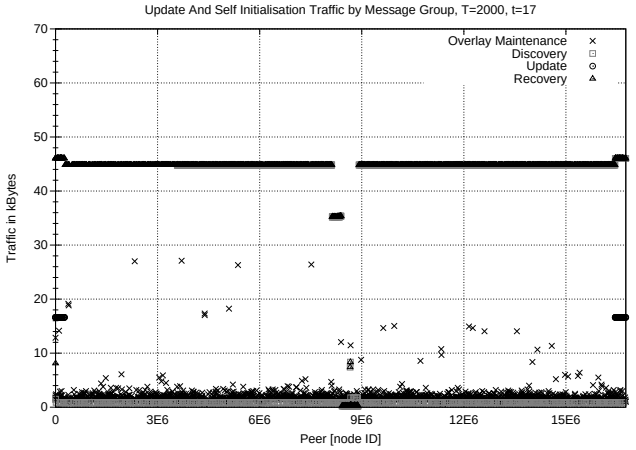
(a) Traffic by message group, T=100, t=16



(b) Traffic by message group, T=500, t=17



(c) Traffic by message group, T=1000, t=17



(d) Traffic by message group, T=2000, t=17

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