Content Privacy Enforcement Models in Decentralized Online Social Networks: State of Play, Solutions, Limitations, and Future Directions

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Abstract

In recent years, Decentralized Online Social Networks (DOSNs) have been attracting the attention of many users because they reduce the risk of censorship, surveillance, and information leakage from the service provider. In contrast to the most popular Online Social Networks, which are based on centralized architectures (e.g., Facebook, Twitter, or Instagram), DOSNs are not based on a single service provider acting as a central authority. Indeed, the contents that are published on DOSNs are stored on the devices made available by their users, which cooperate to execute the tasks needed to provide the service. To continuously guarantee their availability, the contents published by a user could be stored on the devices of other users, simply because they are online when required. Consequently, such contents must be properly protected by the DOSN infrastructure, in order to ensure that they can be really accessed only by users who have the permission of the publishers. As a consequence, DOSNs require efficient solutions for protecting the privacy of the contents published by each user with respect to the other users of the social network. In this paper, we investigate and compare the principal content privacy enforcement models adopted by current DOSNs evaluating their suitability to support different types of privacy policies based on user groups. Such evaluation is carried out by implementing several models and comparing their performance for the typical operations performed on groups, i.e., content publish, user join and leave. Further, we also highlight the limitations of current approaches and show future research directions. This contribution, other than being interesting on its own, provides a blueprint for researchers and practitioners interested in implementing DOSNs, and also highlights a few open research directions.

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1. Introduction

Decentralized Online Social Networks (DOSNs) [1] have been proposed as alternative solutions to the currently widespread centralized Online Social Networks (OSNs) because they give back to the users the control on their own data. As a matter of fact, the most popular OSNs are based on centralized architectures, where service providers (e.g., Facebook, Twitter, or Instagram) have the full control over the data published by their users, thus increasing the risk of censorship, surveillance, and information leakage [2]. DOSNs, instead, are typically based on a P2P architecture (such as a network of trusted servers, or a Distributed Hash Table), where there is no central service provider which has full control on user data. For instance, Diaspora [3], one of the most popular DOSNs which attracted about 400K users [1], is based on a network of independent and federated servers that are provided and managed by the users themselves. Hence, DOSNs give back to users the control over the contents they publish by storing these contents on users’ devices, and by running an instance of the service on these devices as well. For the above reasons, DOSNs have to adopt efficient and effective solutions for guaranteeing contents availability on the one hand, and contents privacy on the other hand [4]. To guarantee their availability, the contents of each user are typically kept available on the DOSN by replicating them on the devices of a number of other users that are online, and by migrating them on the devices of other online ones as soon as the former go offline. This strategy raises relevant privacy and security issues, because the users hosting the contents of other users on their devices could not be actually authorized to access those contents according to the privacy preferences of the publishers. Consequently, DOSNs require the definition of proper security strategies and mechanisms to preserve contents privacy.

Most of the popular DOSNs, in an effort to help users smoothly regulate content sharing in adherence to their privacy preferences, allow to organize users in groups. In this way, each user can choose to share the contents she/he publishes only with the users belonging to a given group. Groups are widely adopted in social networks for several purposes [5]. For instance, some DOSNs allow their users to define some kind of groups typically aimed to link together a number of users who have the same interests (such as sports, school, work, hobbies), enabling content sharing among them. The creator is the group administrator, and the other users either have to ask for being admitted, or they are invited by the administrator. Once members, users can publish contents (such as posts, images, or videos) that will be reserved only to the other members of the group. Another kind of groups are the ones that are defined by users to organize their...

[1] https://diasp.eu/stats.html
contacts into a private address book, typically according to circles [6] or the type of relationships with them (e.g., schoolmates, colleagues, family, acquaintances, etc.). These groups can be seen only by the user who defined them [7, 8], who can restrict the access to the contents she/he published to the members of one or more of her/his groups. The privacy enforcement models adopted by existing DOSNs to guarantee the privacy of the contents are very different from each other, each one having its own pro and cons. For instance, several approaches [9, 10, 11, 12, 13, 14] allow their users to define groups and exploit encryption mechanisms for making contents visible only to the members of the group they are reserved to. Consequently, such approaches are typically computationally demanding both for publishing and accessing contents and, especially, for changing the privacy preferences.

1.1. Motivations

In the last few years, several papers have been devoted to review the available literature on decentralized privacy preserving mechanisms for DOSNs, analysing several aspects of such approaches. In the following, we briefly mention the most
important ones, highlight the main differences between them and with respect to the work proposed in this manuscript.

Table 1 summarizes in a convenient format the distinguishing features taken into account by the previously surveys on DOSNs, namely: the privacy enforcement models to protect users’ contents (Privacy enforcement model), the definition of an analytical cost-model describing the overhead introduced by the privacy preserving mechanisms implementing the enforcement models (Theoretical model), and the experimental evaluation of the privacy preserving mechanisms (Experimental evaluation). In particular, the works proposed in [15, 16, 17] were among the first ones to provide an overview of current privacy preserving mechanisms to ensure the independence from the centralized service provider in DOSNs. However, they do not take into account the privacy enforcement models used by DOSNs for contents sharing, but mainly focus on investigating the architecture used to allow independence from the centralized service provider [15], the types of social information that have been used to improve the design of current DOSNs [16], and the major technical aspects that prevent widespread adoption of current DOSNs [17].

Authors of [18] study the impact caused by design decisions in DOSN architectures. The work is mainly intended to investigate the general architectural models of DOSNs while the privacy enforcement models of the different solutions are only slightly described.

The work proposed in [19] identifies a set of criteria that are used to construct a taxonomy for the classification of DOSNs. Architecture, types of service, social application development, availability and scalability are among the most important criteria discussed by the authors. As per the security criteria of DOSNs, they mainly focused on the authentication, the confidentiality of messages, and the data integrity.

Authors of [22] provide literature review of about 165 papers related to DOSNs by focusing on how decentralization is achieved and the advantages/disadvantages of decentralization. They analyse the decentralized designs of current DOSNs and cluster them based on their infrastructure, network topology, authority relations, and privacy properties. In particular, the main privacy property considered in the paper is the confidentiality from both third parties and peers. The work proposed in [21] investigates how current DOSNs manage contents generated by users, discussing the data format and describing the type of privacy mechanisms used to protect them.

Recently, authors of [20] provide a comprehensive survey on DOSNs, discussing their technical requirements and the mechanisms used to define the overlay network. However, the problem of protecting the privacy of contents in DOSNs has been partially addressed in [20] because they only focused on listing security features provided by DOSNs.

A discussion of the privacy and architectural features provided by current DOSNs is presented in [23], where authors mainly focused on investigating their suitability for mobile devices.

Instead, authors of [24] compare and discuss available literature on privacy preserving mechanisms for DOSNs based on three main areas: data storage and
replication, data access control management, and fake accounts and fake content management. The work does not cover in more details the characteristics of the privacy enforcement models and, as authors claim, there is still need for more research efforts, especially w.r.t. dynamic group membership management.

The work proposed in [26] provides fine-grained classification of various state-of-the-art approaches related to data privacy, data integrity, and secure social search solutions for DOSNs.

Another relevant work for user’s privacy is proposed in [25], where the authors survey the features of the most important privacy policy languages available in current literature for representing privacy preferences of users.

Finally, in [27] the authors analyse the most popular DOSNs and, for each of them, they describe the specific features and architectural choices, analyse the privacy enforcement models, and formulate an analytical cost model for evaluating the complexity of executing the main operations on groups (adding/removing a member, publishing a content) in terms of number of group members.

Despite most of the popular DOSNs adopt groups-based solutions for preserving contents privacy, Table 1 reveals that none of the available works provides a complete evaluation of the main current privacy enforcement models w.r.t. the different privacy requirements characterizing distinct types of groups defined in DOSNs. In fact, only the authors of [27] present an analytical cost model evaluating the complexity of executing the main operations on groups in several privacy enforcement models adopted in DOSNs. However, they do not provide an experimental assessment of such cost-models which, instead, is actually the best way to find which privacy enforcement models are suitable for efficiently implementing the privacy requirements characterizing each group type.

Hence, this work is motivated by the fact that the design of DOSNs privacy enforcement models deserves to be further analyzed in terms of suitability to accommodate the peculiar privacy requirements of groups defined in the DOSNs, taking also into account performance aspects.

In particular, the main differences between this paper and the existing ones, are highlighted in the following. First, we do not compare DOSNs among themselves. Instead, we first extract a set of features idiosyncratic for each DOSN, and later propose a taxonomy of the user groups based on the cited privacy requirements—note that user groups are typically adopted in DOSNs (and in OSNs in general) to define privacy preferences. Moreover, based on the above introduced taxonomy, we identify three main classes of privacy enforcement models representing the solutions adopted by most of the currently available DOSNs and, for each of the cited classes, we analyse how the privacy requirements for each of the group types could be implemented. Finally, we perform an extensive set of experiments based on realistic simulations to evaluate the real applicability of such solutions. In particular, we experimentally evaluate how the privacy requirements defined by the different group types affect the cost of executing the main operations on groups in each privacy enforcement model. Open research directions are also highlighted.
1.2. Contributions

The main novel contribution brought by this paper is an extensive analysis of the solutions adopted to preserve contents privacy in existing DOSNs following an alternative approach with respect to the existing surveys. This way, we are able to shed light on some of the less known aspects of privacy in DOSNs, as well as to provide a solid experimental support for the performance of the most common functionalities provided by the different models. Some novel research directions are also discussed. In detail, we provide the following contributions:

1. We study the features of the user groups provided by current DOSNs, and we identify 4 different types of groups, each having different requirements related to content privacy;

2. We classify the privacy enforcement solutions adopted by the existing DOSNs for protecting user contents into three main models. The first privacy enforcement model \([9, 10, 11, 12, 13, 14]\) exploits encryption mechanisms for making contents visible only to the members of the group they are reserved to. The second privacy enforcement model is still cryptography based, and it improves the performance of the DOSN platform by adopting a hierarchical data structure for a smart management of encryption keys \([28, 29, 30, 31, 32, 33]\). The third privacy enforcement model, instead, avoids content encryption by adopting proper content allocation and replication strategies. In particular, contents remain unencrypted, but they are stored on the devices of the content owner or of trusted (or authorized) users only \([34, 35, 36, 37, 38, 39]\);

3. We study the capability of each of the 3 previously listed privacy enforcement models to implement the 4 types of groups available in DOSNs;

4. We execute a set of experiments based on realistic models simulations to give an estimation of the overhead introduced by the 3 privacy enforcement models in performing the typical DOSN operations (publication of a content in a group, user joining or leaving a group) on each of the group types we defined;

5. We compare the costs of the 3 privacy enforcement models obtained from our experiments in order to find which is the most suitable one for implementing each of the group types we defined. We believe that this is the best way of making a realistic comparison among the 3 privacy enforcement models. We highlight the lessons learned from our analysis, providing important information for increasing effectiveness and efficiency of privacy enforcement models;

6. We provide interesting future research directions and discuss open challenges.

It is worth noting that, in order to reduce the analysis to a manageable dimension, while preserving the generality of results, rigor, and formalism, the following approach was selected. Once the relevant policies of interest to manage privacy in DOSNs are identified, we focused on the representative mechanisms instrumental to implement the related privacy enforcement models. As such,
we were called to choose among the many privacy enforcement mechanisms available. We decided to go for the most used ones, because of their representativeness and possible impact of our findings. Note that the choice, while reducing the domain to a manageable dimension, does not hamper either the generality or applicability of the achieved results, given the fact that all of the selected mechanisms fully represent the expressiveness of the underlying policy.

1.3. Outline

The contributions previously defined, as well as the general structure of the manuscript, are graphically represented in Figure 1. In particular, the remainder of this paper is organized as follows. In Section 2 we characterize the properties of current DOSNs by providing a taxonomy for groups (based on operations, group type, and backward secrecy property), that will be used to structure the evaluation of the privacy enforcement models. In Section 3 we introduce the reader to the typical privacy solution adopted by DOSNs (Encryption-based, LKH-based, and Allocation-based). In Section 4 we describe how the selected DOSNs’ solutions implement the privacy policies enforcement during the execution of the typical operations (group join, group leave, and content publish) and how they implement the modification of such policies. In Section 5 we illustrate the evaluation of the selected approaches taking into account the messages and the encryption/decryption operations required to execute the previously listed DOSN typical operations, while in Section 6 we compare the performance of the different approaches and discuss their advantages and limitations. In Section 7
we draw future research directions, i.e., based on the recent advent of blockchain technology, the adaptivity, and the hierarchy property. Finally, in Section 8 we report some conclusions.

2. DOSNs: A Characterization

In order to allow their users to protect the contents they publish, current DOSNs enable them to specify their privacy preferences to determine who can access each of these contents. The typical privacy controls provided by the most part of existing DOSNs are based on the group communication model, where a user shares his/her contents with a previously defined group of users. Despite its simplicity, this privacy model involves communication between a user, the content producer, and a possibly large set of contacts, i.e., the members of the group. In addition, each DOSN service implements its own type of groups, by providing variants of this basic setting. In this section, we investigate the characteristics of the groups provided in existing DOSNs and, based on the identified characteristics, we defined a taxonomy for groups that will be used to structure the evaluation of the privacy enforcement models in DOSNs.

Since we are interested in analyzing privacy enforcement models which restrict access to contents, we do not consider public groups where anyone can see all contents without restrictions. Indeed, groups exposing their contents publicly to all users do not need to regulate access to such contents. Instead, for non public groups, the main common characteristics we identified are: the scope, the visibility of the membership information, the number of administrators of the groups, the enforcement of the backward secrecy property for the join and leave operations, and which users are allowed to publish contents on
the group (group owner or all members). Figure 2 graphically represents these characteristics as well as the options within each of them.

As concern the scope, DOSNs enable users to create groups in order to either organize their own contacts in a private address book (such as, Safebook [7] or Vis-a-Vis [8]) or to create a community for connecting users among them (such as, groups in LifeSocial.KOM [10], ProofBook [30], or LibreSocial [41]). In the first case, groups are privately defined by the group creator based on the relationship he/she has with the group members (such as, family members, classmates, or colleagues), and the members are not aware of the groups they belong to, they cannot see the other members of the group, and they cannot decide to join/leave them or to publish a content in the group, because these groups are for the exclusive use of the group creator. Hence, each DOSN user sees and uses only the set of groups he/she created, which is different from the set of groups defined by the other users.

Instead, community groups are meant to build communities where users interact by sharing contents with other users, typically having the same preferences (such as, the supporters of a football team or a political party). In this case, DOSN users are able to see the groups created by the other users, and they explicitly ask (or they are asked by) the administrators to join such groups, thus being always aware of belonging to a community group.

At the time of creation, the group owner indicates whether the group is administrated also by other members. If the group is configured to be managed collaboratively by multiple users, then the group owner must specify the identity of the other administrators.

The group owner can also select the initial members of the group and must configure the visibility of the membership information. In particular, the group owner can decide to reveal the identities of the group members to everyone (i.e., public), to group members only (i.e., protected) or to no one else than the group owner (i.e., private). It should be noted that in the case of private membership information, the members of a group are not aware of the group itself, they simply have access to the content shared in that group, seeing them as contents published by the group owner. We identify three operations involving groups typical of DOSNs: publication of contents in a group, join of a new user to a group, and leave of a member from a group.

*Publication of a content.* the publication of contents on a group determines the privacy level of such contents. Indeed, by publishing a content on a group, the content producer gives access rights to all (and only) the members currently belonging to these groups. Depending on the configuration of the group, it can accept for publication contents created by the group owner or by any of the group members.

*Group Join.* Groups defined in DOSNs are dynamic because new members can be added to the group. The join operation involves at least the group owner and the users who are being added to the group. It can be either initiated by the group owner or requested by a user who does not yet belong to the
Table 2: Mapping of the types of groups available in DOSNs

| OSN          | Join Backward Secrecy | Leave Backward Secrecy | Group Scope | Publish | Admin | Membership |
|--------------|------------------------|------------------------|-------------|---------|-------|------------|
| Safebook [7] | x                      | x                      | community   | ✓       | ✓     | ✓          |
| PeerSoN [9]  | x                      | ✓                      | community   | ✓       | ✓     | ✓          |
| LibreSocial  | x                      | ✓                      | community   | ✓       | ✓     | ✓          |
| Vis-a-Vis [8]| x                      | x                      | group owner | ✓       | ✓     | ✓          |
| ProofBook [10]| x                     | x                      | community   | ✓       | ✓     | ✓          |
| Contrail [12]| ✓                      | x                      | community   | ✓       | ✓     | ✓          |

If the join operation is successfully executed, a new user is added to a group in order to allow her/him to access the new contents that will be posted to this group. Consequently, every time a new user is added to a group, the membership information needs to be updated, in order to ensure that the new member can access such contents. Instead, the contents published in the group prior to the join of the new user can be made either accessible (join without backward secrecy) or not accessible (join with backward secrecy) to the joining member.

**Group Leave.** An existing member of a group can be removed at any time by the group owner in order to deny her/him the access to the new contents that will be posted to the group (forward secrecy), or can voluntarily decide to leave the group. As a consequence of the group leave, the group membership information needs to be updated in order to ensure that the removed member cannot access the new contents that will be posted on this group after the execution of the remove operation. Instead, the contents published in the group before the execution of the remove operation can be either still accessible (leave without backward secrecy) or not (leave with backward secrecy) to the removed member through the DOSN infrastructure.

Unlike the join operation, which requires asynchronous interaction between the group owner and the joining user, the leave operation is initiated by either the group owner or the leaving user, and it typically does not need any other action from the leaving user.

Table 2 summarizes the features of the group types supported and implemented by a subset of the most popular existing DOSNs, where the taxonomy is used to classify each group. We can observe that existing DOSNs support a very heterogeneous set of groups having different characteristics. For instance, the majority of the DOSNs allow their users to create groups based on community that do not support the backward secrecy on the join operation, i.e., they allow a joining user to access all the contents previously published in the group. Instead, groups aimed to organize contacts are provided by few DOSNs.
### Table 3: Mapping of the types of groups available in centralized OSNs

| OSN       | Join Backward Secrecy | Leave Backward Secrecy | Group Scope | Publish | Admin | Membership |
|-----------|------------------------|------------------------|-------------|---------|-------|------------|
|           |                        |                        | all members | group owner | individual | collaborative | public | protected | private |
| Anobii    | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| Chess     | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| LinkedIn  | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| Goodreads | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| Fotki     | ✓                      | ✓                      | priv addr book | ✓    | ✓   | ✓          |
| Flickr    | ✓                      | ✓                      | priv addr book | ✓    | ✓   | ✓          |
| Fitocracy | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| Facebook  | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| Ning      | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| Printerest| ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |
| Twitter   | ✓                      | ✓                      | community   | ✓        | ✓     | ✓          |

(i.e., Safebook [7] and Vis-a-Vis [8]) and they have private membership information because they are used by owners to regulate the access to the contents they share. For what concerns the group leave operation, most of the existing DOSNs allow the users removed from a group to still access the contents published prior to the execution of the leave operation (leave without backward secrecy). In a few number of DOSNs (such as PeerSoN [9] and LibreSocial [41]), instead, the group leave operation revokes the access rights to these contents to the removed members (leave with backward secrecy). In this case, although after the execution of the leave operation the DOSN prevents the removed members from accessing such contents anymore, this cannot be really considered as an effective countermeasure for protecting the privacy of such contents. As a matter of fact, the removed users could have created a local copy of such contents on their local nodes when they had the right to do that, and such copies will be always available to them. Hence, we could state that a group leave fully guaranteeing backward secrecy is not possible.

Furthermore, although this paper is focused on DOSNs, we noted that the taxonomy for groups we defined actually have general characteristics, which are common to groups implemented by existing centralized OSNs as well. For instance, Table 3 summarizes the group types commonly supported and implemented by a subset of the most popular centralized OSNs. We observe that the type of group supported by the most part of current OSNs, such as Facebook, Flickr, Twitter, and LinkedIn allows a joining user to access all the contents previously published in the group, while former members cannot access anymore the contents published in a group if they leave (or are removed from) it.

Based on the combination of the previous common characteristics shown in Figure 2, 4 different types of groups can be defined and, in the following, we focus only on the most common ones. Table 4 summarizes the types of
Table 4: Characteristics of the types of groups considered in our analysis

| Group Type | Join Backward Secrecy | Contents visible to the joining user | Leave Backward Secrecy | Contents visible to the removed user | Publis. Admin | Membr. |
|------------|------------------------|-------------------------------------|------------------------|-------------------------------------|---------------|--------|
|            | Old New | Old New | Old New | Old New | members | individual | public |
| G1         | ✓       | ✓       | ✓       | ✓       | ✓             | ✓             | ✓       |
| G2         | ✓       | ✓       | ✓       | ✓       | ✓             | ✓             | ✓       |
| G3         | ✓       | ✓       | ✓       | ✓       | ✓             | ✓             | ✓       |
| G4         | ✓       | ✓       | ✓       | ✓       | ✓             | ✓             | ✓       |

Groups considered in our analysis, by specifying the type of operations (join, leave, and publish), the contents visible to the joining/removal users, the type of administration and membership. In particular, let \( t \) the time when a join or leave operation terminates successfully, we define the set of contents published on the group before time \( t \) as old contents. Instead, the contents published on the group after time \( t \) are referred as new contents. Groups of type G1 ensure that both the removed and the joined users cannot be able to access old contents published in the group. Since, this type of groups does not found use in current DOSNs (and OSNs), it is not considered in our analysis. Groups of type G2 ensure that the new member cannot access old contents published in the group. Instead, the leave operation on groups of type G2 allows the removed user to still access the contents previously published in the group. Groups of type G3 ensure that a member removed from the group cannot access old contents published in the group. Instead, the join operation on groups of type G3 allows the new user to access both future and old contents published in the group. Finally, groups of type G4 allow a new member to access the contents already published on the group before she/he joined, and a removed member can still access the contents published in the group before the removal operation. As concern the publication of the contents, the group administration, and the membership of the group, we consider the case where contents can be published by all members of the groups, only the group owner is responsible for the administration of the group, and the memberships information are public. Indeed, as shown in Table 2 and 3, such configuration have been found wide spread usage in most DOSNs (more than 50%), and OSNs in general.

3. Classification of the content privacy enforcement models

Although several DOSNs exist in current literature, the most part of the solutions they adopt to protect content privacy can be classified into three distinct types of privacy enforcement models: Encryption-based, Allocation-based, and LKH-based. Without loss of generality, we can assume that the selected privacy enforcement models allow users to protect the contents they publish by defining the group of users who can access these contents. As a matter of fact, Section 2 shows that a very common solution to express privacy preferences in DOSNs
Table 5: Summary of the enforcement models proposed in the current literature

| Encryption-based       | LKH-based         | Allocation-based       |
|------------------------|-------------------|------------------------|
| PeerSoN [9]            | LKH+TGDH [31]     | Vis-a-Vis [8]          |
| LifeSocial.KOM [10]    | DOSN LKH [28, 32] | My3 [44]               |
| DECENT [13]            | LKH+OFT [30]      | DiDuSoNet [39]         |
| SocialGate [12]        | Shi R.H. et al. [14] | Privacy Policy [35, 39] |
| LotusNet [13]          | ELK [45]          | Trust [39]             |
| Contrail [12]          | OFT [33]          | Zeng S. et al. [46]    |
| ProofBook [10]         | LKH [29]          | eXO [44]               |
| Safebook [7]           | DGKD [48]         | Solid [49]             |
| SuperNova [14]         |                  | Bortoli S. et al. [50] |
| LibreSocial [41]       |                  |                        |
| BCOSN [51]             |                  |                        |
| WebP2P [52]            |                  |                        |
| Megaphone [53]         |                  |                        |
| SEDOSN [54]            |                  |                        |
| ReClaim [55]           |                  |                        |
| PSON [56]              |                  |                        |

(and OSNs) is the definition of groups of users. An alternative solution to specify the users who can access a content is the one that expresses privacy preferences through attribute-based access control policies. Each privacy enforcement model adopts a specific technique to enforce such privacy preferences. Table 5 summarizes the privacy enforcement models adopted by a number of existing DOSN platforms and by the approaches proposed in the scientific literature, and in the following, we describe in more detail such models.

3.1. Encryption-based approaches

The typical solution for the enforcement of content privacy adopted by a large number of DOSN is to have each group \( G \) paired with its symmetric encryption key \( K_G \), which is created by the group owner and distributed to the members of \( G \) when they join the group [57]. In this way, each member of \( G \) is able to publish a content addressed to the other members of \( G \) by encrypting it with the symmetric group key \( K_G \) before being stored on the peers of the DOSN. Consequently, the members of group \( G \) use \( K_G \) for accessing the contents published in the group. For instance, PSON [50], Safebook [7], LotusNet [13], Contrail [12], ProofBook [10], SuperNova [14], and Megaphone [53] exploit the symmetric group key to encrypt all the contents shared in a group, i.e., \( C_0, C_1, ..., C_n \).

Instead, a similar approach is exploited by PeerSoN [9], LifeSocial.KOM [10], Cachet [11], DECENT [13], SocialGate [12], LotusNet [13], SuperNova [14], LibreSocial [41], and BCOSN [51], which create a new specific symmetric key, \( K_C \), for each content to be protected, i.e., \( C_i \) with \( i \in \{0, 1, ..., n\} \). In this case, each content is encrypted with the corresponding symmetric content key \( K_C \), which is, in turn, encrypted with the symmetric group key \( K_G \).
The most part of current DOSNs exploit asymmetric encryption (such as, PeerSoN [9], Safebook [7], LifeSocial.KOM [10], LibreSocial [11]) or Attribute Based Encryption (ABE) (such as, Cachet [11], DECENT [13], SocialGate [12], SEDOSN [53], and BCOSN [54]) to securely distribute the symmetric group key $K_G$ to the members of group $G$.

An encryption-based approach is also used in [52, 55], where asymmetric cryptography is now used to protect the confidentiality of contents.

3.2. LKH-based

The LKH-based enforcement model enhances the encryption based one exploiting a hierarchical structure for managing symmetric group symmetric keys, such as Logical Key Hierarchical Tree [29] (LKH). This structure is used to reduce the cost of redistributing the symmetric group key to the group members when it is updated, as shown in Section 5. For instance, the approach proposed in [28, 32] exploits the LKH Tree proposed in [29]. When a group $G$ is created, the group owner creates the related key-tree $KT(d,h,G)$, where $d$ is the maximum number of children for a node. Each node of $KT$ is paired to a symmetric key and each group member is paired to a leaf of $KT$. In particular, a leaf node is paired with a symmetric user key, the root of the tree is paired with a symmetric group key while the intermediate nodes are paired with symmetric intermediate keys. As for the other cases, each user of the DOSN is paired to an individual asymmetric key-pair. The main characteristics of the group are stored and kept available by the DOSNs storage system while the $KT$ is stored on the local device of the group owner. The idea behind this approach is that the group owner manages the $KT$, updating it every time a new user joins the group or a member leaves it. The join or removal of a user also requires the group owner to redistribute both the symmetric group key and the symmetric intermediate keys of $KT$ located on the path from the root to the leaf representing the removed/joined user, as described in more details in Section 4.

Authors of [31] proposes a decentralized group key management algorithm which combines the LKH and the TGDH scheme. In particular, a group of $n$ users is divided into $s$ subgroups, each with $n/s$ members. Each subgroup is managed by an individual LKH scheme while TGDH is employed for inter-subgroup key management. Every node of the TGDH is paired with a symmetric secret key and a blinded key. Finally, One-way Function Tree (OFT) schemes [33] are also bases on the LKH approach but OFT assigns keys on the tree based on the key of the parent [30].

A similar approach is exploited by Shi R.H. et al. [44], where a large group is divided into several subgroups, each managed by a subgroup key manager. A group key generator center is in charge of managing all the key manager, generating, distributing and updating group keys for secure communications by all group members.

Authors of [45] proposed ELK, a secure group communication protocol which combines LKH and OFT mechanisms. The DGKD protocol proposed by [48] adopts a tree structure where the leaf key of a node is paired the public key of the corresponding group member while all
the intermediate nodes are paired to symmetric secret keys. The protocol introduces also the concept of sponsors and co-distributors. The former are group members initiating the key generation and rekeying process. The latter, are group member that receive the new keys from the sponsor and help distribute the new keys to group members.

The key management approaches for secure group communication have been also proposed and studied in different contexts and scenarios (such as, centralized and distributed architectures). A complete review of such approaches is presented in [59].

3.3. Allocation-based

In the Allocation-based enforcement model, the privacy of the contents is enforced by implementing a privacy preserving content storage strategy. The idea behind this model is to avoid encryption of contents still preserving the producers’ privacy preferences by properly choosing the peers of the DOSN (replica peers) where allocating contents.

Some approaches, such as the one proposed in [37, 38] and extended in [39], exploit the privacy preferences defined by the producer of a content \( c \) in order to select a set of replica peers where a copy of \( c \) can be stored. In particular, such replica peers are chosen among the ones that belong to users who are allowed to access \( c \) according to the privacy preferences defined for \( c \). In this way, if one user tries to directly access the unencrypted contents stored in his/her device bypassing the DOSN infrastructure, she/he cannot acquire more information than the ones she/he is allowed to access according to contents’ privacy preferences.

Instead, a number of DOSNs such as Solid [49], eXO [47], Vis-a-Vis [8], My3 [34], DiDuSoNet [36], and [60, 50] select the replica peers by simply asking their users to select a set of trusted peers in the DOSN. In this case contents are replicated on the peers belonging to users explicitly declared as trusted by the contents producers.

The system proposed in [46] exploits blockchain to verify the correctness of the data and users contents are stored in clear on both the local database of the contents’ owners and the random selected peers. Finally, authors of [35] exploits sociological trust model derived from real OSNs (known as the Dunbar model) to automatically select the set of devices trusted by users. The Dunbar trust model relies on the fact that users establish relationships with different levels of intensity (strong or weak ties) and the interactions occurred on social relationships can be used to measure the degree of trust between individuals [61].

In the following, we focus on Allocation-based enforcement models where the replica peers are selected according to the privacy preferences defined by users. Indeed, such allocation mechanism does not introduce a risk for the privacy of the contents because the users asked to store a copy of a given content are among the ones authorized to access it.

Finally, replica peers are in charge of enforcing the security preferences expressed by the producers of the contents they store. As a matter of fact, when
a user \( v \) requests access to the content \( c \), the replica peer storing \( c \) evaluates the privacy preferences of the content in order to decide whether to allow \( v \) to access \( c \).

4. Privacy Preferences Enforcement Models

In this section, we briefly describe how the privacy enforcement models defined in Section 3 can be exploited by current DOSN systems in order to support the definition of different types of groups commonly used in DOSNs and OSNs, namely, the groups G2, G3, and G4 discussed in Section 2. In particular, we select a representative approach for each enforcement model of Section 3 and, for each of them, we discuss how the following three operations are implemented: content publish, group join with/without backward secrecy, and group leave with forward secrecy and with/without backward secrecy.

Since users can disconnect from the system at any time, all the approaches we selected exploit a Distributed Hash Table (or DHT [62]) to enable asynchronous communication between users, even if one of the parties is disconnected from the DOSN.

4.1. Encryption-based enforcement model

The reference approach we take into account for the Encryption-based enforcement model is the one that have each group \( G \) paired with its symmetric group key, \( K_G \), which is created by the group owner and securely distributed to the group members [9, 10, 11, 43, 12, 13, 14, 41, 51].

In addition, each group is also paired to a shared data structure: the Group Message List (i.e., a message list kept available by the DHT), exploited by the group administrator to notify all group members with messages containing symmetric group key that have been updated. Instead, direct messages between the group administrator and a group member are exchanged by using a Private Mailbox service [63, 64] implemented by the DHT. In particular, each user \( u \) is paired to a Private Mailbox data structure which supports the append operation and allows the other users to append new (encrypted) messages (such as notifications or private messages).

4.1.1. Content publishing

In the reference scenario considered, all the members of a group \( G \) can publish a content \( c \) in the group. In particular, the content producer creates a new symmetric content key, \( K_c \), to protect \( c \). In fact, the content \( c \) is encrypted with the symmetric content key \( K_c \), while the current symmetric group key, \( K_G \), is used to encrypt and securely communicate \( K_c \). Finally, the encrypted content is published on the DOSNs, i.e., stored along with the encrypted symmetric content key on a number of peers of the DHT.
4.1.2. Group Join

Without backward secrecy. The join without backward secrecy is used to implement groups of type G3 and G4. As shown in Table 2 and 3, the group join operation provided by almost all the considered DOSNs and OSNs does not provide backward secrecy. The Encryption-based approach where the join operation does not support backward secrecy is quite easy to implement. In particular, when a new user is added to a group, the group owner does not change the current symmetric group key. The group owner simply encrypts the symmetric group key to the joining user by encrypting it with the public key of the joining user and stores the encrypted message on the Private Mailbox of the joining user.

In order to join the group, the joining user retrieves the message containing the encrypted group key from the Private MailBox and decrypts it by using her/his private key. Since the symmetric group key does not change when a new user is added to the group, both the old and the future contents that were/will be published in the group are/will be accessible to the new member, as well as to the already existing members of the group.

With backward secrecy. The join with backward secrecy is used in groups of type G2. In the Encryption-based enforcement model, the join operation with backward secrecy must change the group key every time a new user is added to the group. As a result, when a new user is added to a group, the group owner creates a new symmetric group key that will be used to encrypt the contents that will be shared for this group from this moment on. The group owner encrypts the new group key with the public key of the joining user and stores the encrypted message to the Private MailBox of the joining user. In order to join the group, the joining user retrieves the new symmetric group key and decrypts it by using his/her private asymmetric key. Since the already existing content published in the group are encrypted with the old group key, the new member cannot access them. In order to communicate the new symmetric group key to the already existing members of the group, the group owner encrypts it with the old group key and stores the encrypted message in the corresponding Group Message List.

4.1.3. Group Leave

In the Encryption-based approach, when a user leaves the group, the group owner updates the symmetric group key, and sends it to the remaining group members in encrypted form, i.e, the group owner asymmetrically encrypts the new symmetric group key with each individual public key of the members remaining in the group. Finally, each encrypted copy of the new symmetric group key is stored on the Private MailBox of each member remaining in the group. The new group key will be used to protect new contents that will be published in the group. Consequently, future content published in the group can be accessed only by the members of the group who received the new symmetric group key (forward secrecy).
Without backward secrecy. In most of the existing DOSNs, the group leave operation does not guarantee the backward secrecy property because it is used to implement groups of type G2 and G4. In the Encryption-based approach, the leave operation without backward secrecy can be implemented by simply changing the current group key when a user leaves the group, leaving the already published contents unchanged. As a result, those users who are members of a group when a content is published will be enabled to access such content forever. Hence, the removed member can still access the contents published in the group when she/he was a group member because such contents remain encrypted by exploiting the old symmetric group key. Instead, the removed member will not be able to access the content published after the leave operation because they will be encrypted with a new group key she/he does not know.

With backward secrecy. The Encryption-based approach can also provide the leave operation with backward secrecy, which is used to implement groups of type G3. In this case, besides changing the current group key to guarantee the forward secrecy property, the group owner needs to update all the contents already published in the group by re-encrypting them with a new symmetric content key which, in turn, is encrypted with the latest group key. Hence, in case of groups with a large number of contents and/or where the members change frequently, this solution is very expensive from the computational point of view, because it requires to re-encrypt all the contents every time a member leaves the group. We also recall that, besides being computationally expensive, this solution does not really protect content privacy, as explained in Section 2.

4.2. LKH-based enforcement model

The reference approach we take into account for the LKH-based enforcement model used for our evaluation is based on [28, 32] and it exploits the Logical Key Hierarchical Tree data structure.

As for the Encryption-based enforcement model, private messages between the group administrator and a group member are exchanged by using the Private Mailbox service. Similarly, each group is also paired to a shared data structure: the Group Message List (i.e., a message list kept available by the DHT), exploited by the group administrator to notify all group members with messages containing the parts of the Logical Key Hierarchical Tree data structure that have been updated.

4.2.1. Content publish

The implementation of the content publish operation supporting the LKH-based enforcement model is quite the same as the implementation supporting the Encryption-based one. A group member creates a content $c$ to publish in the group, which is paired with an LKH data structure. In order to share the content in the group, the content producer creates a new symmetric content key, $K_c$, to protect $c$, encrypts $c$ with $K_c$, and uses the current symmetric group key paired to the root of the LKH to encrypt $K_c$. Finally, the encrypted content and content key are published on a number of peers of the DHT.
4.2.2. Group Join

Without backward secrecy. The LKH-based enforcement model can be easily adopted in order to implement the join operation without guaranteeing backward secrecy, used in groups of type G3 and G4. In fact, since the joining user should have access to all the contents already published in the group, adding a new user to the group simply means that the current symmetric group key is shared with the new user. In particular, as shown by Figure 3(b), to add the user $U_4$ to the group, the group owner $o$ simply creates a new leaf node $K_{U_4}$ of the key tree $KT(d, h, G)$ for $U_4$, while the symmetric keys of the existing nodes remain the same. The group owner securely communicates the nodes of $KT$ from the root $K_{123}$ to the leaf $K_{U_4}$ to the joined user by using the Private Mailbox of $U_4$. In particular, the group owner exploits the asymmetric public key of $U_4$ to asymmetrically encrypt the symmetric leaf key $K_{U_4}$, and uses the symmetric leaf key $K_{U_4}$ to symmetrically encrypt the rest of the keys paired to the nodes on the path from the father of $U_4$ to the root of the $KT$.

The group owner does not send anything to existing members of the group because the nodes of $KT$ concerning them have not been changed.

With backward secrecy. In order to guarantee backward secrecy in groups of type G2, each time the group owner $o$ adds a new user $U_4$ to the group $G$, $o$ must change the symmetric group key paired with $G$ and must communicate
the new key to U4 and to the previously exiting group members. In this way, o prevents U4 from accessing the contents previously published in the group. To this aim, o updates the key tree KT by changing the symmetric group key paired with the root of KT, K_{123}, and by adding the leaf node K_{U4} corresponding to the new user. Figure 3(a) shows how the key tree KT is reorganized when the user U4 joins the group, and the nodes of KT highlighted in red color are the ones that are created or updated because of the join operation. In order to ensure backward secrecy, o also updates the symmetric keys of the nodes on the path from the new root K_{1234} to the joining node K_{U4}. Then, the group owner communicates these keys to U4 by exploiting the Private Mailbox of U4. In particular, to securely transfer such keys, the group owner encrypts the symmetric leaf key K_{U4} by using the asymmetric public key of U4, and uses the symmetric leaf key K_{U4} to symmetrically encrypt the rest of the keys paired to the nodes on the path from the father of U4 to the root of KT. Instead, to communicate the updated keys (including the group key) to the existing members of the group, the group owner encrypts each of them with its previous version, and creates a message including all such encrypted updated keys which is sent to group members by storing it on the Group Message List.

Once she/he received such data from o, U4 exploits her/his asymmetric private key to decrypt the symmetric leaf key K_{U4}. Then, the key K_{U4} is used to decrypt the new symmetric intermediate key K_{34} and the new symmetric group key, K_{1234}, which is paired with the root. This key will be used by U4 and by the other users for the publication of the new contents of the group and for accessing them. The new symmetric group key, K_{1234}, does not reveal anything about the contents published before U4 joined the group, because they have been encrypted with the previous version of such key (K_{123}).

Finally, the existing members of the group who have some nodes on the path from their leave to the root of the KT updated, exploit the old versions of the keys of such nodes to decrypt the new version of such keys. This is also valid for the new symmetric group key K_{1234} of the KT, which can be decrypted by existing members using the key K_{123}.

4.2.3. Group Leave

Without backward secrecy. The leave operation without backward secrecy used in groups of type G2 and G4 can be easily implemented by the LKH-based enforcement model. Indeed, when a member leaves the group, the group owner removes the corresponding leaf from the key tree (see Figure 4) and updates the symmetric keys of the nodes along the path from the root to the father of the removed leaf (including the symmetric group key). In particular, supposing that the user U4 leaves the group, the group owner removes the leaf K_{U4} of the user from the key tree and updates the symmetric keys of the nodes along the path from the root K_{1234} (i.e., the symmetric group key) to the father of the removed leaf, K_{34}. Figure 4 shows the key tree resulting from the leave operation while the updated nodes are highlighted in red color. The group owner creates a notification message and stores it in the Group Message List in order to distribute such new node keys to the members left in the group. The notification message
Figure 4: Graphical description of the LKH-based leave operation with and without backward secrecy.

consists of such updated keys, each of which is encrypted with the keys on their children nodes. This encryption procedure starts from the father of the node corresponding to the leaving user, and proceeds towards the root of the KT in order to guarantee that the key of each node is encrypted with the latest versions of the keys of its children nodes. As a result, future contents of the group will be encrypted with the new symmetric group key, which is unknown to the removed user. The removed user can still access the old contents published in the group by exploiting the old symmetric group key.

With backward secrecy. The LKH-based enforcement model can be easily adapted to implement group G2, providing a leave operation with backward secrecy. In order to guarantee the forward secrecy property, when a member U4 of a group G leaves the group (see Figure 4), the symmetric group key must be changed following the same procedure described for the group leave without backward secrecy. Moreover, in order to ensure that the removed member cannot access the old contents published in the group, the group owner must re-encrypt all the contents by exploiting the new symmetric group key created in the previous step. For this reason, the group owner retrieves all the contents already published in the group, decrypts them by exploiting the old symmetric group key $K_{1234}$, obtaining the plain contents. Then, the group owner re-encrypts each content by using a new symmetric content key which is, in turn, encrypted with the current group key $K_{123}$. Finally, the group owner store the contents on the storage service of the DOSNs. As a result, the removed user cannot access the current version of the contents published in the group because they are encrypted with a new content key and a new group key. Again, we recall that this solution does not really protect content privacy, as explained in Section 2.

4.2.4. Lessons learned

The analysis of the LKH-based enforcement model allowed us to learn several lessons that are worth mentioning in this section.
Table 6: Strategies for the maintenance of data structure in the LKH-based enforcement model

| Rekeying strategy | Rekeying time | Issues                  | Advantages              | Applications      |
|-------------------|---------------|-------------------------|-------------------------|-------------------|
| individual        | immediately   | - scalability           | + security              | OSN, healthcare,  |
|                   |               | - out-of-sync           | + easy to implement     | messaging         |
|                   | periodically  | - rekey interval        | + low cost              | teleconferencing, |
|                   |               | - security              | + customizable          | pay-per-view,     |
|                   |               |                         |                         | pay-tv, streaming |

**Maintenance of data structure.** The data structure used in the LKH-based enforcement model changes over time because of users joining and leaving the group. For this reason, the efficiency of the model depends on whether the underlying data structure remains balanced. Several works [65, 66, 67, 68] have focused on proposing new algorithms to reduce the rekeying cost and they can be classified into two groups, depending on the proposed rekeying strategy. Table 6 summarizes the characteristics of the strategies used for the maintenance of the data structure. In individual rekeying strategy [66, 67, 69] the operation for updating the data structure (known as rekeying) must be performed whenever a member joins or leaves the group. In particular, the key used to encrypt the data is changed immediately and the sender has to reveal some secrets to each receiver in order to enable the reconstruction the data. For this reason, the suffers from scalability issue in the case of dynamic groups, because several new keys may be generated, distributed, but not used by the group members. In addition, the out-of-sync problem is also present in individual rekeying strategy because a group member could receive a content encrypted with a group key that it has not received yet. However, this strategy is very easy to implement and ensures that the users joining/leaving the group can/cannot instantly access to the content published in the group after their addition/removal. Consequently, the individual rekeying strategy is suitable to be used in several scenarios that are relevant for the security and privacy, e.g., online social network, healthcare, and messaging applications.

The batch rekeying strategy [68, 65, 70, 71] is another approach used to reduce the overhead of the join and leave operations and it consists in executing the rekeying periodically, only when a certain number of requests have been collected. For the join operation, the rekeying of the data structure can be executed either when a number of requests are ready to be processed or a new content is published on the group. However, the leave operation exposes a critical security issue because the removed users can still get access to the contents published on the group until the rekeying of the data structure has been performed [68]. Another important issue for the batch rekeying strategy, is to determine a proper rekey interval, i.e., the length of the time interval to wait
for group access/removal requests [72]. In addition, the batch rekeying strategy introduces a lower overhead compared to the individual rekeying strategy and it can be dynamically adapted to the behavior of group members. For these reasons, the batch rekeying strategy is widely used in the field of teleconferencing, pay-per-view, and streaming applications.

**Optimal tree structure.** An important task in the key tree model is to find the optimal configuration parameters of the data structure for a certain pattern of user behaviors, minimizing the cost of individual or batch updates. The approaches used to solve this problem are summarized in Table 7 and they aim to model the optimal parameters of the key tree for a specific rekeying strategy and problem setting.

For instance, the works proposed in [73, 74] investigate the optimal tree structure with minimal cost for individual rekeying strategy in the case of a single deletion. Instead, the authors of [74, 75, 76, 77, 78, 68] focused on the optimal tree structure for the batch rekeying strategy. In particular, authors of [74, 75] study the degree bound for the problem of deleting two users while authors of [76, 77] investigate the optimal tree structure under the assumption that $k$ members arrive in the initial setup period and only member deletions are allowed after that period. Authors of [68] prove that 4 is the best key degree under the assumption that the batch consists of $k$ joins and $j$ leaves. Instead, the work proposed in [79] study the optimal data structure when the size of a batch is not large and each user has a fixed probability $p$ of being replaced during the batch period. Finally, authors of [78] extended the work of [79] by considering also the case of loyal users, i.e., users who have zero probability to leave the group.

### 4.3. Allocation-based enforcement model

The Allocation-based enforcement model considered for our evaluation is based on the approaches described in [37, 38, 39]. These approaches protect the privacy of a content $c$ by taking into account the privacy preferences defined by the content owner in order to choose the replica peers for storing the copies of $c$. Indeed, with respect to other models, such approach guarantees that contents will be always stored on the replica peers belonging to users who are authorized to access them. For this reason, content encryption is not necessary. Moreover, in [37, 38, 39], the privacy preferences of the users are specified in XML through the XACML standard [80], and they are stored in a policy repository, called Policy Administration Point (PAP) according to the XACML reference architecture. Whenever a privacy policy is created or updated by a user, the group owner has to notify it to the policy repository by sending the updated data.

In order to compare the Allocation-based enforcement model with the previously described ones, in the following we suppose to have an XACML privacy policy for each group, consisting of a set of identity-based privacy rules, one for each content published in the group, which lists the identities of the members who are authorized to access such content. Hence, in this scenario the list of peers authorized to access the content $c$ is explicitly available, thus making not
necessary to evaluate the policy on a (possibly very large) set of candidates to find the peers for storing the copies of \( c \).

In the following, we discuss how the operations content publish, group join and group leave can be implemented.

4.3.1. Content publish

In the Allocation-based enforcement model, a group member creates a content \( c \) and a privacy rule for \( c \) which lists the identities of current group members who are authorized to access the content \( c \). Then, the group member asks the PAP to add such rule to the privacy policy of the group. Once the content will be published, the privacy policy of the group will be evaluated each time a user will request to access it, by using the authorization component of the privacy-preserving framework. Such component checks whether the requesting user actually holds the required access right and returns authorization decision. Moreover, to guarantee the availability of contents, the privacy policy of the group is evaluated by using the authorization component of the privacy-preserving framework in order to define the set of peers that can host a replica of such contents. As matter of fact, each content \( c \) is replicated by the allocation
mechanism of the DOSN on a number of peers of authorized users available in the system.

4.3.2. Group Join

With backward secrecy. The Allocation-based enforcement model is well suited to implement the join operation with backward secrecy provided by groups of type G2. As a matter of fact, when a new member joins a group, the group owner updates the list of the current group members with the identity of the new user, and each new content that will be published on the group after the join of the user will be paired to a privacy rule which grants access to the identities of both the new user and the members that were already in the group. Instead, to guarantee backward secrecy, the privacy rules of the group privacy policy related to the contents already published in the group remain the same, i.e., they only grant access to the old group members while they deny access to the joining user. As a result, the joining users cannot access the contents published in the group before she/he joined it.

Without backward secrecy. The Allocation-based enforcement model can be easily adapted to implement join operation without backward secrecy provided by groups of type G3 and G4. As in the previous case, when a new user joins the group, the group owner updates the list of current group members by adding the identity of the new user. As a result, the joining user will be able to access future contents that will be published on the group because a new rule will be added to the group privacy policy for such contents which grants access to both the joining user and the members that were already in the group. In addition, in order to not have the backward secrecy, the group owner must ensure that the new user can access also the old contents published in the group. For this reason, the group owner must update the privacy rules paired to the contents already published in the group as well, by adding the ID of the new user among the IDs of the authorized ones.

4.3.3. Group Leave

Without backward secrecy. The Allocation-based enforcement model is well suited to implement the leave operation without backward secrecy provided by groups of type G2 and G4. As a matter of fact, when a member leaves the group, the group owner removes the intended user from the list of the current group members so as to guarantee that he will not be allowed to access the contents that will be published in the future (forward secrecy). The rules of the group privacy policy related to the existing contents of the group remain the same, so that the removed user can still access the corresponding contents.

With backward secrecy. The Allocation-based enforcement model can be adapted in order to implement a leave operation with backward secrecy, as provided by group G3. As in the previous case, to ensure the forward secrecy property, when a user leaves the group, the group owner removes the intended user from the list of the current group members so as to guarantee that she/he will not
be considered as authorized member for the publication of future contents. In order to ensure also the backward secrecy property, the group owner changes the rules of the group privacy policy related to the contents already published in the group to deny the access to the leaving user as well.

4.3.4. Lessons learned

The analysis of the Allocation-based enforcement model provided us with new insights and highlighted challenges that are summarized below.

**Data storage management.** The Allocation-based enforcement model takes advantage of a data storage model to ensure that authorized users can access unencrypted contents they are interested in and several proposals of data storage managements for DOSNs exist. Figure 5 classifies the data storage management approaches used in the Allocation-based enforcement model. In general, existing approaches assume that the underlying storage service responsible for data management is either implemented in a decentralized way by the DOSNs [31, 36, 35, 37, 38, 39, 47] or provided by a centralized entity [8, 46, 50, 49]. In the case of a centralized data storage management, the DOSN assumes that users have cloud-computing utility that is used for running virtual machine instance implementing the OSNs services. For instance, Vis-a-Vis [8] provides a virtual machine instance running in a paid cloud-computing utility such as Amazon Elastic Compute Cloud (EC2) or Rackspace Cloud Servers while Zeng S. et al. [46], Bortoli S. et al. [50], and Solid [49] require an accessible storage repository, which can be deployed on personal servers by the users themselves, or on any cloud storage provider (e.g., Dropbox). The users must trust the centralized provider of the storage service because it can access any user data. In addition, the cloud-computing utility should support a Trusted Platform Module [51] for verifying the software stack running under the instances.

Instead, in the case of a decentralized data storage management, the contents generated by users can be stored either on their local devices [47] or on the other users’ devices automatically selected by the DOSN, based on different factors (such as, trust relationships between users [31, 36, 35] or privacy policies defined by users [37, 38, 39]).

**Data availability.** Another important challenge for the Allocation-based enforcement model is to keep the contents available as much as possible while...
Figure 6: Summary of the workflow used by the Allocation-based enforcement model to guarantee the availability of the contents.

securing them from unauthorized access by other users. In the case of a centralized data storage management, such as Vis-a-Vis [8], Zeng S. et al. [46], Bortoli S. et al. [50], and Solid [49], the users are responsible for configuring the quality of service offered by cloud provider by specifying upload and download bandwidths or cloud downtime. Consequently, the data availability and the reliability of the data storage service is guaranteed by the cloud provider, which ensures also the compliance with agreed terms of the service. In contrast to the previous approach, the decentralized data storage management stores the contents on some users’ devices which can disconnect from the system whenever they want. For this reason, the classical approach used to increase the availability of the contents is to replicate a copy of them on different users’ devices. An overview of the general workflow for guaranteeing data availability in P2P system was described in [82]. However, in order to discuss all the challenges of the data availability for the Allocation-based enforcement model, we further refine the general workflow for data availability as shown in Figure 6. The first phase of the workflow is to properly select the devices on which to store users’ contents according to different types of information which could improve the availability and the security of the data. For instance, authors of [36, 35] select the devices based on the trust relationships and the online time period of the user while authors of [34] exploits also geographical locations. Instead, the approach proposed in [37, 58, 39] selects the devices according to trust information derived by the privacy policies defined by users. Once the device is selected, the data storage phase is responsible for storing a copy of the content on the selected device while the data verification phase periodically checks if the device
(and the contents stored on it) remains available in the system. When content is no longer available a data repair phase is executed, which retrieves a copy of the content and repeat the entire workflow.

5. Experimental evaluation

In order to evaluate the three privacy preferences enforcement models (Encryption-based, Allocation-based, and LKH-based), we developed a set of simulations by using the P2P Peersim simulator. For each privacy enforcement model, the simulation implements the corresponding reference approach described in Section 4 and creates several groups of types G2, G3, and G4 in order to evaluate its performance. As observed in Section 2, the groups of type G1 are not considered in our analysis because this type does not found use in current DOSNs and OSNs. For each type of group, we evaluate separately the operation of content publication, group join, and group leave, varying the number \( n \) of members in the group. In particular, we consider groups having \( n \) equal to 10, 50, 100, 1000, and 10 000 and we suppose that they are obtained by a sequence of join operations. For the content publication operation, the number \( p \) of contents to be published in each group is set to 10, 50, and 100. For the group join and leave operations, we consider the addition or removal of a single user from several groups having different number of contents and members.

For each operation and privacy enforcement model, we measure the execution cost for the group owner, for the joining/leaving users, and for the other members in terms of time spent to execute the operation and number of bytes sent and received. We consider contents of size \( c \) fixed to 100KB, since it is the maximum image size you can upload on Facebook.

In the Allocation-based enforcement model, the Balana open source framework is used as reference implementation of the XACML standard specification and for the evaluation of the privacy policies. Moreover, we assume that each peer hosts its own PAP, which stores the privacy policies of all the groups related to the contents stored by such peer.

The LKH-based enforcement model creates a key-tree (\( KT \)) for each group \( G \). In the following, when we measure the costs of this enforcement model, we do not account for the overhead that would be needed to keep such key-
Table 9: Cost of the symmetric encryption algorithms provided by the Crypto++ Library

| Algorithm       | Throughput (MB/s) | Cycles/Byte | Setup Key (µs) | Setup Key (cycles) |
|-----------------|-------------------|------------|----------------|-------------------|
| AES/CTR (256-bit key) | 2496              | 0.8        | 0.278          | 611               |
| AES/CBC (256-bit key)  | 447               | 4.7        | 0.216          | 475               |

tree balanced. In particular, such an approach is justified by the following reasons: (i) tree re-balancing operations typically occur in batch, when a given number of evictions is reached [S3]; (ii) the rate of leave is not triggered by m2m communications, but mainly by humans, as such the total number of evictions is not expected to be relevant over relatively short period of times [S4]; (iii) when the rate of join and leave is roughly balanced, the tree data structure does not need frequent re-balancing, since join basically contribute to keep it balanced [S5]; and, finally, (iv) the balancing operations could occur during periods of low utilization of the data structure. For the above cited reasons the introduced overhead can be considered manageable, and hence we will not consider it, while we will focus on the overhead related to the management of the core operations for the different scheme under analysis.

The implementation of the symmetric and asymmetric scheme used by the LKH-based and Encryption-based enforcement models we exploit the Crypto++ library [5], a well-known open-source cryptography library written in C++ which implements many ciphers with consistently good performance on all of them. Table 9 summarizes the performance of the symmetric cryptographic algorithms considered by the enforcement models investigated in this manuscript. For each cryptographic algorithm we reported the following performance measures: the number of MB encrypted/decrypted per second (Throughput), the number of cycles-per-byte required by encryption/decryption (which depends upon the CPU frequency), and the number of microseconds (µs) and cycles required for key setup. The cryptographic algorithm based on symmetric schema does not increase the size of the encrypted data compared to the input data and it can be used with a CTR configuration block mode or with a CBC configuration block mode [S6]. Instead, Table 10 summarizes the performance of the asymmetric cryptographic algorithms considered by the enforcement models investigated in this manuscript. For each cryptographic operation, we reported the number of millisecond and the number of Megacycles required for its execution. Since asymmetric encryption is used by privacy enforcement models only to protect symmetric keys of length 256 bit, all tests were done by using 2048-bits RSA keys and by repeating the crypto operations over blocks of random data having a size comparable to such keys. Consequently, the output of the asymmetric encryption operation has size equal to that of the RSA key length (i.e., 2048

[5] https://www.cryptopp.com/
Table 10: Cost of the asymmetric encryption algorithms provided by the Crypto++ Library

| Operation                  | Milliseconds | Megacycles |
|----------------------------|--------------|------------|
| RSA 2048 Encryption       | 0.16         | 0.29       |
| RSA 2048 Decryption       | 6.08         | 11.12      |
| RSA 2048 Signature        | 6.05         | 11.06      |
| RSA 2048 Verification     | 0.16         | 0.29       |

![Figure 7: Evaluation of the number of cryptographic operations taken by LKH-based and Encryption-based enforcement model for the publication/retrieval of different number of contents.](image)

bits), even when the input data size to encrypt is less than 2048 bits.

The test platform exploited for our experiments is a PC equipped with an Intel Core i7-2.20 GHz CPU, 8GB or RAM, running Linux Ubuntu. In addition, the cryptographic algorithm based on symmetric schema has been configured to use the CTR configuration block mode.

5.1. Content publish

In this subsection we evaluate the cost of publishing contents in a group in the three enforcement models. In general, this cost depends on the size of the group, \(n\), and on the number of contents to publish, \(p\).

For the LKH-based enforcement model, the publication of \(p\) contents on a group of size \(n\) requires a number of symmetric encryption operations equals to twice the amount of content published, i.e., \(2 \cdot p\). Indeed, the content producer creates a new symmetric content key for each content, performs a symmetric encryption operation to encrypt the content (100KB) with this content key, and a second symmetric encryption operation to encrypt the content key (256 bits) with the group key. As a result, two symmetric encryption operations are executed for each content published (see Figure 7).

The cost for publication of contents of the Encryption-based enforcement model is the same as the LKH-based. Indeed, in the Encryption-based enforcement model as well, a group is paired with a symmetric group key which is used to securely distribute the symmetric content keys exploited to encrypt the contents published on the group. In both the LKH-based and Encryption-based enforcement models, the encrypted content and the related encrypted
content key are then replicated on the peers of the DOSN, for instance by using a DHT.

Publishing a content in a group the Allocation-based enforcement model requires the creation of the related rule to be embedded in the group privacy policy. As previously explained, in order to compare the implementation of the Allocation-based enforcement model proposed in [37, 38, 39] with the implementations of the Encryption-based and LKH-based ones, where the privacy preferences definition is based on groups, in our evaluation tests we enforce a XACML policy which mimics a group by checking whether the ID of the user requesting the access to a content is included in the list of the IDs of the members of the group. Consequently, the peers used to host the replicas of each content are simply chosen from such list of IDs, thus not requiring additional computational cost w.r.t. the other two enforcement models where the replicas can be stored anywhere. A copy of the privacy policy of a group is stored on the PAP of each peer hosting contents of such group, and such policy is evaluated every time a user requests to access the content, in order to ensure that only the right group members can access it. Figure 8(a) shows the average time (in ms and 95% C.I.) required for the creation of a privacy policy intended for groups

Figure 8: Allocation-based enforcement model: Figure 8(c) shows the time taken by the user in order to evaluate privacy policy on groups with different number of users and contents. Figure 8(b) shows the total size (in KB) taken by the privacy policies paired to the groups, while Figure 8(a) shows the average time required for the creation of privacy policies.
of different number of members and varying the number of contents. The time introduced for the creation of the privacy policy is negligible and it increases with the number of users of the group. Figure 8(b) shows the total size (in KB) taken by the privacy policies paired to groups consisting of different number of users and contents. In particular, the graph has a log scale and it clearly indicates that the size of a privacy policy paired to a group depends on both the number of users and contents already published in the group. Indeed, each content published in the group is paired to a rule of the group privacy policy which grants access to such content to the right members of the group. In order to evaluate the overhead introduced by the group privacy policy enforcement when accessing a content, Figure 8(c) shows the average time needed to create the XACML request (denoted as request creation) and to evaluate the group privacy policy varying the number of members of the group and the number of contents published within the group. The time required to create the XACML request is constant because it contains mainly the identifier of the applicant and the identifier of the requested content. Instead, the evaluation time of the group privacy policy depends on both the number of contents published in the group and the number of authorized users listed in the policy.

Figure 9 summarizes the costs introduced by the three enforcement models for publishing a content on a group G of \( n \) members. The plot does not include the cost for replicating the content on a number of peers of the DOSN. As shown in Figure 9(a), the LKH-based and the Encryption-based enforcement models take the same time for the publication of the content, i.e., 0.225 ms, regardless of both the size of the group and the number of contents already published in the group. As previously explained, the number of symmetric encryption operations involved during the publication of a content is equals to 2: an encryption operation on the symmetric content key and an encryption operation on the corresponding content. The most part of the overhead introduced by Encryption-based and LKH-based approaches during the publication is spent on content encryption. As shown in Figure 9(b), the LKH-based and the Encryption-based enforcement models result in the same number of data sent. Indeed, the content publisher sends at most 2 messages: the former to retrieve the last version of the group key and the latter to publish the new encrypted content along with the encrypted content key. As a result, since the size of symmetric keys is fixed to 256 bits in our tests, the amount of data sent depends mainly on the size of the content (which is 100KB in our tests).

Instead, the cost of publishing a content in the Allocation-based enforcement model (see Figure 9(a)) is due to the creation of the new rule of the group privacy policy that grants the access right to the published content to all the current members of the group. Since we already observed that the policy creation time depends mainly on the number of group members, we fixed the number of contents already published in the group to 10. In Figure 9(a) we observe that the time taken by Allocation-based enforcement model is considerably lower than those of the other two approaches and, in general, the overall time required by the approaches still remain negligible. However, this plot does not include the time required to replicate the content on a number of peers of the DOSN.
5.2. Group Join

This section evaluates the cost of the three enforcement models to perform a group join operation, i.e., to add a new user to a group, varying the size of such group. In particular, in the following, we evaluate separately the cost of the join operation both in the case when the backward secrecy property is guaranteed, and when it is not ensured.

Join with backward secrecy (G2). The join operation ensures the backward secrecy property when the new member of the group is not allowed to access the contents previously published for the group. Figure 10 shows the average time and the number of bytes spent by the different actors of the DOSN due to the procedure performed to add a user to a group, varying the number of members of such group.

In order to ensure the backward secrecy in the Encryption-based and in the LKH-based enforcement models, each time the group owner \( o \) adds a new user \( a \) to the group \( G \), \( o \) also changes the symmetric key of the group \( G \) in order to prevent \( a \) from accessing the contents previously shared with the existing members of \( G \).

If the Encryption-based enforcement model is adopted, the new group key is securely distributed to the new user by asymmetrically encrypting it using AES/CTR (256-bit key) and RSA 2048.
the new user’s public key, while the old \( a \) members of the group receive the new group key symmetrically encrypted utilizing the old symmetric group key. As a result, the group owner performs one symmetric and one asymmetric encryption operations and sends a total of 2 encrypted symmetric keys. As shown by the Figure 10(a), the time needed by the group owner in order to add a user to the group is constant and does not depend on the number of group members.

The number of bytes sent by the group owner is also constant (about 350 bytes) and it is shown in Figure 10(b). In particular, an asymmetrically encrypted packet of 256 bytes is sent from the group owner to the joining user in order to communicate the new symmetric group key, while the remaining bytes are necessary to distribute the new symmetric group key (and other information) to the old members (through symmetric encryption). The joining user, instead, has to retrieve the new symmetric group key and to decrypt it by using her/his private key. For this reason, the number bytes received by the joining user (see Figure 10(d)) is equal to the size of the asymmetric public key (2048 bits) and the most of the time is spent for the asymmetric decryption (see Figure 10(c)). Similarly, each of the already existing members of the group have to retrieve the encrypted message containing the new symmetric group key and to decrypt it by using the old symmetric group key (see Figure 10(e) and 10(f)).

In the case of LKH-based approach, the group owner creates a new key for the group, updates the LKH tree as described in Section 4, and properly distributes the new keys to the joining user and to the already existing group members. In particular, the group owner creates a new leaf node of the LKH tree \( KT(d, h, G) \) to represent \( a \), and changes the symmetric keys of the nodes on the path \( P_a \) from the root (included) of the key tree to the new leaf representing \( a \). Hence, the number of nodes on \( P_a \) is, at most, equal to \( h + 1 \), where \( h \) is the height of the LKH tree. Since we assumed the LKH tree balanced, we have that \( h = \lceil \log_d(n) \rceil \).

To communicate the nodes on \( P_a \) to \( a \), the group owner encrypts the relevant node contents and uses the Private Mailbox of \( a \). In particular, the groups owner asymmetrically encrypts the content paired with the leaf representing \( a \) (including the symmetric individual key of \( a \)) with the public key of \( a \), and symmetrically encrypts the other \( h \) nodes of \( KT(d, h, G) \) on \( P_a \) with the symmetric individual key of \( a \). As a result, the group owners performs \( O(h) \) encryption operations with the symmetric schema and only one encryption operation with the asymmetric schema. In addition, to communicate to the previously existing group members the \( h \) keys refreshed along the path \( P_a \), \( a \) encrypts each node on this path with its old symmetric key, thus performing at most \( O(h) \) symmetric encryption operations. Hence, the total number of nodes encrypted by the group owner with a symmetric schema is equals \( O(2 \cdot h) \), while the total number of keys encrypted with an asymmetric schema is equal to 1. Figure 10(a) shows the amount of time required by group owner in order to set up the new symmetric keys and to perform such encryption operations. nodes encrypted using symmetric schema and 1 node protected by using asymmetric encryption schema based on 2048 bits key length.

The joining user \( a \) receives the \( h + 1 \) encrypted nodes along \( P_a \) of the key
tree and executes $O(h)$ symmetric decryption operations and one asymmetric decryption operation on them. As shown by Figure 10(c), the majority of time is spent on the asymmetric decryption operation. Instead, the sum of bytes received by the joining user is due to both the asymmetrically encrypted packet of 256 bytes and the symmetrically encrypted $h$ nodes along the path $P_a$ (see Figure 10(d)).

The existing members of the group retrieve the updated nodes along $P_a$, each encrypted with the corresponding old symmetric key. Each member of the group has to decrypt only the involved nodes along its path. Figure 10(e) shows the average time required by the existing members of the group in order to
decrypt the updated nodes of their interest. The members of the group have to decrypt only the involved keys along their path (i.e., at most $h$ keys in the case the member is paired with a sibling node of the one paired to the joining user). As shown by Figure 10(f), the sum of bytes received by a group member is less than those received by the joining user, i.e., equals to $O(h)$ nodes encrypted by using symmetric schema.

In the Allocation-based enforcement model the group owner has to update the membership information by considering the new user in the group. As a result, a new content that will be published on the group will be paired to a privacy rule that considers also the identity of the new joining user. As shown by the Figure 10, the join of a user with the Allocation-based enforcement model involves only the group owner and it does not require expensive operation because the group owner update only local membership information about the group.

**Join without backward secrecy ($G_3, G_4$).** When the join operation does not support backward secrecy, a joining user can access all the contents previously published in the group. The LKH-based and the Encryption-based enforcement models can easily provide a join without backward secrecy by simply communicating the current symmetric group key to the joining user $a$. To this aim, with the LKH-based approach, the group owner $o$ creates a new leaf node of the key
tree $KT(d, h, G)$ for $a$. The symmetric keys of all the nodes of the key tree, including the root, remain the same. In order to send to the joining user the nodes of the key tree she/he needs, the same approach previously described for the join with backward secrecy is adopted. In particular, the leaf corresponding to the joining user (embedding the individual symmetric key of such user) is asymmetrically encrypted with her/his public key, while the nodes on the path from the father of the leaf paired to the joining user to the root (including the group key) are symmetrically encrypted with such individual symmetric key. As a result, the total number of nodes sent by the group owner is at most $h + 1$. In particular, the group owner executes $O(h)$ encryption operations with the symmetric schema and only one encryption operation with the asymmetric schema. Figure 11(a) shows the time required by group owner to add a new user to a group. The cost is mainly due to the execution of the asymmetric encryption operation. The message created by the group owner for the joining user contains $O(h)$ nodes protected with symmetric encryption and a leaf node protected by using asymmetric encryption based on 2048 key length. As shown by Figure 11(b), the number of bytes sent by the group owner is logarithmic with respect the number of group members. The joining user receives the $h + 1$ nodes along her/his path, hence executing $O(h)$ symmetric decryption operations, while the number of asymmetric decryption is equals to one. As shown by Figure 11(c), the majority of time is spent to perform the asymmetric decryption operation (which costs considerably more that the corresponding encryption operation), while the sum of bytes received by the joining user, shown in Figure 11(d), is equal to the sum of bytes sent by the group owner (see Figure 11(b)).

We observe that, supposing that a reorganization of the key tree is not required to insert the new user’s leaf, the execution of the join operation without backward secrecy does not involve the other members of the group because all the symmetric keys of the key tree remain the same.

Instead, the Encryption-based enforcement model requires only the distribution to the joining user of the symmetric group key, which, to maintain its confidentiality, is asymmetrically encrypted before being transferred by using the joining users’s public key. As a result, the group owner perform only one asymmetric encryption operation and sends a single encrypted message of 256 bytes, which consists of the symmetric group key encrypted by using a public key of 2048 bits (see Figure 11(a) and 11(b)). The joining user retrieves such message containing the encrypted group key (see Figure 11(d)) and decrypts the symmetric group key by using her/his private key (see Figure 11(c)). The join of a user does not introduce any cost for the other members of the group.

Finally, in order to add a user to a group with the Allocation-based enforcement model, the group owner adds the joining user to the list of the identities of the current group members to enable the user to see the contents that will be published on the group from that moment on. In addition, in order to allow the joining user to access the contents that have already been published in the group, the group owner properly modifies also the privacy rules paired to the contents already published in the group. Hence, in the Allocation-based enforcement model, the execution of the join operation without backward secrecy...
Figure 12: Evaluation of the time and the number of bytes spent by the group owner and the existing members for the leave without backward secrecy of a user from groups with different numbers of members.

involves the group owner only. Figure 11(a) shows the time spent by the group owner in order to add the joining user to the current group member list and to update the policies of the contents already published in the group, while Figure 11(b) shows the number of bytes (in log scale) sent by the group owner as a result of the join operations. The plot, confirms that the time and the number of bytes sent by the group owner depends only on the number of contents published in the group, because the group owner has to grant to the joining user the access to all the contents already published in the group. For the join without backward secrecy, the Allocation-based enforcement model does not introduce any cost for the joining user and for the existing members of the group.

5.3. Group Leave

In this section, we evaluate the cost for removing a member from a group (leave operation) varying the number of members and contents. The leave operation always guarantees the forward secrecy property, i.e., the evicted member will not be able to access the contents that will be published in the group after the execution of the leave operation.
Leave without backward secrecy \((G2,G4)\). When the leave operation does not guarantee backward secrecy, the member removed from the group is still able to access the contents published in the group before her/his leave.

In order to remove a member from the group \(G\) with the LKH-based enforcement model, the group owner \(o\) deletes from the key tree \(KT(d,h,G)\) stored on her/his local peer the leaf node corresponding to the removed user, \(r\). To guarantee the forward secrecy property, the group owner refreshes the symmetric keys on the path \(P_r\) from the father of the removed leaf to the root (including the symmetric group key). Since the height of the key tree is equal to \(h\), the number of nodes on the path \(P_r\) is, at most, equal to \(h\). The updated father node of the removed leaf is symmetrically encrypted exploiting the (at most) \(d-1\) keys paired with its remaining children nodes, i.e., the siblings of the removed leaf, in order to securely communicate it to the group members paired to such nodes. Recursively following this approach, i.e., exploiting the symmetric keys paired with the \(d\) children nodes, the new version of each node on the path \(P_r\) is symmetrically encrypted and securely communicated to the related users. As a result, the number of symmetric keys created by the group owner is equals to \(O(h)\) while the number of symmetric encryption operations is at most \(O(d \cdot h)\).

Hence, the group owner creates one message, the leave notification message, which consists of at most \(O(h)\) encrypted nodes and embeds them on the Group Message List in order to send it to the remaining group members. Indeed, Figure 12(a) shows that the time (in log scale) required by the group owner in order to refresh the symmetric keys and encrypt the related nodes does not increase significantly with the size of the group. Similarly, Figure 12(c) clearly indicates that the amount of bytes sent by the group owner is also logarithmic with respect the size of the group and it is at most equals to \(O(d \cdot h)\). Each of the existing members of the group has to retrieve the leave notification message and decrypt only the new symmetric keys on her/his path, i.e., at most \(O(h)\) symmetric keys. As shown by Figure 12(b), the time spent by a member of the group in order to decrypt the symmetric keys along her/his path is negligible and also depends on the position of the removed user in the key tree. As regards the average number of bytes received by the existing members of the group (see Figure 12(d)), each member reads the full leave notification message. Finally, the leave operation does not introduce any cost for the removed user and it does not require the use of asymmetric encryption operation.

When the Encryption-based enforcement model is used, in order to implement the leave operation without backward secrecy, the group owner updates the symmetric group key and communicates the new group key to the members left in the group to protect future contents published in the group. However, the contents already published in the group remain encrypted with the old symmetric group key. As a result, the removed user can still access them by using the old symmetric group keys stored on her/his devices. The new symmetric group key is asymmetrically encrypted with the individual public key of each member remaining in the group. Hence, the group owner performs a number of asymmetric encryption operations which is linear with respect to the number of group members (i.e., \(O(n)\)). Finally, the group owner sends an encrypted copy.
of the new symmetric group key to each member of the group. As shown by Figure 12(a), the time required by the group owner for the encryption of the new symmetric group key is quite big because it involves only asymmetric encryption operations. In addition, the bytes (see Figure 12(c)) spent by the group owner in order to distribute the new symmetric group key linearly increase with the number of group members.

Each member of the group retrieves only the encrypted message which contains the symmetric group key encrypted with his/her public key (equal to 256 bytes). The member decrypts the new symmetric group key by using her/his private key and stores it on her/his device. As a result, each member left in the group performs only an asymmetric decryption operation and store only one symmetric key. Indeed, the amount of the processing time required by the remaining group members for the leave of a user without backward secrecy is constant and does not depend on the number of group members or on the number of contents published in the group (see Figure 12(b)). The number of bytes retrieved by a group member is also constant and equals to the length of the public key (see Figure 12(d)). Instead, the user removed from the group does not perform other any operations to exit from the group.

The Allocation-based enforcement model can be easily adapted to provide the leave operation without backward secrecy. In order to remove a user from the group, the group owner deletes the affected user from the list of the identities of the group members. As a result, the new contents which will be published in the group will be paired to a privacy rule that does not consider the identity of the removed member. In contrast, the privacy rules paired to the contents already published in the group remain the same and they still provide access to the removed user. As shown by the experimental results in Figure 12(a), the time required by the group owner in order to request the removal of a user from the list of the identities of the members of a group is negligible. In fact, Figure 12(c) shows that the number of bytes sent by the group owner is constant and it does not depend on the number of users. Finally, adopting the Allocation-based enforcement model, the leave without backward secrecy does not introduce any cost for the existing members of a group.

Leave with backward secrecy (G3). In order to ensure the backward secrecy property, the leave operation must guarantee that the removed member cannot access anymore the contents already published in the group. When the LKH-based enforcement model is adopted, the forward secrecy is guaranteed by properly updating the key tree as previously described for the leave without backward secrecy.

However, this is not sufficient to guarantee the backward secrecy property as well, because the symmetric contents keys of the $p$ contents published in the group before executing the leave operation are potentially known to the removed user, as well as the old group key with which they are encrypted. As a result, the removed user can still access them. Hence, in order to enforce the backward secrecy on the removed user, the group owner must retrieve the $p$ contents published in the group and re-encrypt them by creating and using $p$ new symmetric
Figure 13: Evaluation of the processing time and the number of bytes spent by the group owner and the existing members for the leave with backward secrecy of a user from groups with different numbers of members and contents.
content keys. Such $p$ new symmetric content keys must then be symmetrically encrypted using the new group key. As a result, the removed user cannot access the new versions of the $p$ contents because they are encrypted with a new content key and a new group key which have not been revealed to her/him. Again, we recall that this solution does not really protect content privacy, as explained in Section 2. Hence, the total number of symmetric encryption operations performed by the group owner is at most equal to $O(2 \cdot p + d \cdot h)$, where $O(2 \cdot p)$ operations are necessary to ensure backward secrecy ($p$ operations are executed on contents and $p$ operations are executed on keys), while $O(d \cdot h)$ operations (executed on key tree nodes) are needed to ensure forward secrecy. Figure 13(a) shows the processing time required by the group owner in order to remove a user while guaranteeing backward secrecy from groups having different number of users (10, 50, 100, 1000, and 10000) and contents (10, 50, and 100). In our experimental setup, the processing time spent by the group owner depends mainly on the number of contents in the group. Indeed, if we compare the time required for updating and encrypting the nodes of the key tree only (shown in Figure 12(a) for the leave without backward secrecy) with the total time shown in Figure 13(a), we observe that the re-encryption of published contents takes more time than those required to update and distribute the updated nodes of the key tree. In addition, Figure 13(c) shows that the number of bytes sent by the group owner in order to remove a user with backward secrecy mainly depends on the number $p$ of the contents published in the group that the group owner has to re-encrypt. Indeed, for all number of contents $p$ and for all the number of group members $n$, more than 99% of the total bytes sent by the group owner are necessary to re-encrypted contents already published on the group.

The existing members of the group retrieve the updated nodes of the key tree from the leave notification message stored in the Group Message List. As shown by Figure 13(d), the number of bytes received in the Group Message List and read by each member of the group is logarithmic with respect the number of users $n$ and correspond to, at most, $O(d \cdot h)$ encrypted nodes of the key tree. Each member $m$ decrypts from the leave notification message at most $O(h)$ nodes, i.e., all the nodes that are in common on the paths from the root towards the two leaves representing $m$ and the leaving member. In addition, the number of bytes read by a member remaining in the group, as a result of the leave operation with backward secrecy, does not depend on the number of the contents $p$ in the group. Indeed, Figure 13(b) shows that the processing time required by a group member in order to decrypt the updated nodes is logarithmic with respect the size $n$ of the group.

In the Encryption-based enforcement model, in order to implement the leave operation with backward secrecy, the group owner removes the identity of the user from the group members list and updates the symmetric group key with a new one. For each of the $n$ members left in the group, the group owner encrypts the new symmetric group key with the individual public key of a member and sends the resulting packet having size 2048 bits to the group member. As a result, the group owner executes $O(n)$ asymmetric encryption operations and
sends $O(n)$ encrypted messages having a constant size that depends on the length of the public key. Finally, the group owner retrieves the $p$ contents already published in the group and re-encrypts each content of the group with a new symmetric content key which is, in turn, encrypted with the latest symmetric group key. As a result, the group owner creates $2p$ new symmetric keys for the contents and performs $2p$ symmetric encryption operations to secure them. Figure 13(a) shows the total processing time required by the group owner for the leave operation with backward secrecy on groups of different number of members $n$ and contents $p$. The results clearly indicate for the groups having $n << p$, i.e., the number of group contents is considerably higher than the number of group members, the processing time mainly depends on the symmetric encryption operations on the contents. However, when $n \geq p$ the processing time mainly depends on the asymmetric encryption operations required to communicate the new symmetric group key to the members of the group. The number of bytes sent by the group owner is mainly affected by the number of contents $p$ of the groups (see Figure 13(c)). Each existing member of the group retrieves the encrypted message of 256 bytes, containing the new symmetric group key encrypted by using public key of the member. Indeed, the Figure 13(d) shows how the number of bytes received by each group member is constant and it does not depend on both the number of members and the number of contents in the group. As shown by the Figure 13(b), the processing time required by each group member is constant and it is equals to the time of an asymmetric decryption operation.

When the Allocation-based enforcement model is used, in order to implement the leave operation, the group owner removes the intended user from the group so as to ensure that she/he will not be considered during the publication of future contents (forward secrecy). Moreover, to ensure the backward secrecy property as well, the group owner updates the privacy rules paired to all the $p$ contents already published in the group, by deleting the identity of the removed users from the list of authorized members. The amount of processing time required to update the privacy policy, as well as its size, depends on the number of contents $p$ published in the group. Indeed, Figure 13(a) shows that the processing time spent by the group owner is very low since it does not require expensive cryptographic operations. In addition, it depends only on the number of contents in the group. The number of the bytes sent by the group owner as a result of the leave operation is the same of the total size of the privacy policy. In particular, Figure 13(c) clearly shows that the number of bytes only depends on the number of contents in the group. Finally, the leave operation with backward secrecy does not involve the existing members of the group but only the group owner.

6. Discussion

The experimental results shown in the previous section provide important information regarding the overhead introduced by the 3 privacy enforcement
Table 11: Comparison of the analytic cost of each privacy enforcement model

| Operation | Group Type | Encryption Costs | LKH Costs | Allocation Costs |
|-----------|------------|------------------|-----------|-----------------|
| join      | G2         | $O(E_{AS} + E_{Sk})$ | $O(2 \cdot h \cdot E_{Sk} + E_{AS})$ | $O(z)$ |
| join      | G3, G4     | $O(E_{AS})$      | $O(h \cdot E_{Sk} + E_{AS})$ | $O(p \cdot z + z)$ |
| leave     | G3         | $O(p \cdot E_{Sk} + p \cdot E_{AS})$ | $O(d \cdot h \cdot E_{Sk})$ | $O(p \cdot w + w)$ |
| leave     | G2, G4     | $O(n \cdot E_{AS})$ | $O(d \cdot h \cdot E_{Sk})$ | $O(w)$ |
| publ.     | -          | $O(E_{Sk} + E_{Sh})$ | $O(E_{Sh} + E_{Sk})$ | $O(n)$ |

\(n\) = number of group members; \(p\) = number of contents in the group; \(d\) = the arity of the key tree; \(h\) = the height of the key tree; \(E_{AS}\) = cost of encrypting a symmetric key using asymmetric encryption; \(E_{Sk}\) = cost of encrypting a symmetric key using symmetric encryption; \(E_{Sc}\) = cost of encrypting a content using symmetric encryption; \(z\) = cost of adding a user to the member list of the group; \(w\) = cost of removing a user from the member list of the group.

models discussed in this manuscript. In this section, we highlight the differences among these privacy enforcement models in terms of costs introduced for each operation. Table 11 compares the performance of the 3 models by showing the analytical costs of the group join and leave operations, and of the content publication on each group type from the perspective of the group’s owner. In the cost expressions reported in Table 11 we denote by \(E_{Sk}\) the cost of encrypting a symmetric key using symmetric encryption, by \(E_{Sc}\) the cost of encrypting a content using symmetric encryption, and by \(E_{AS}\) the cost of encrypting a symmetric key using asymmetric encryption. Instead, \(n\) is the number of member of the group, \(p\) is the number of contents published in the group, \(d\) represents the maximum number of children nodes of a node in the LKH-based enforcement model and \(h\) is the height of the key tree. Moreover, \(z\) and \(w\) indicate the complexity to add/remove a user to/from the member lists, respectively.

From Table 11 we observe that the time complexity introduced by the Encryption-based enforcement model for the group join operation on groups of type G2, G3, and G4 is constant, i.e., it does not depend neither on the number of members belonging to the group nor on the number of content published it the group. As a matter of fact, in case of group of type G3 or G4, the cost of the join operation is due to one asymmetric encryption operation, \(E_{AS}\), involving the existing group key, and its transmission to the new member. In case of groups of type G2 a new group key is created, and one symmetric encryption operation (which costs \(E_{Sk}\)) is performed to securely transmit such new group key to the existing users, while one asymmetric operation (which costs \(E_{AS}\)) is executed to transmit the same new group key to the new member. For what concerns the group leave operation, its execution cost when the group does not support backward secrecy (i.e., groups of type G2 or G4) depends on \(n\), the number of members of the group, because \(n\) asymmetric encryption operations (which cost \(n \cdot E_{AS}\)) are executed to distribute the new group key to the remaining users. In case of group of type G3, where backward secrecy is supported, the cost is higher and also depends on the number of contents \(p\) already published in the group because, besides redistributing the new group key (which costs \(n \cdot E_{AS}\)), each content is also re-encrypted using a new symmetric
content key (the additional cost is $p \cdot E_{sk}$) and each new symmetric content
key is encrypted by using the new symmetric group key (the additional cost is
$p \cdot E_{sk}$). Finally, the cost for the publication of a content is also constant and
it does not depends on the number of members in the group but it depends
only on the size of the published content. Indeed, the content is encrypted with
a new symmetric content key (which costs $E_{sc}$). Instead, the new symmetric
content key is encrypted by using the symmetric group key (which costs $E_{sk}$).

The cost of the LKH-based enforcement model for the group join operation
depends on the height $h$ of the key tree, i.e., which is logarithmic in the number
$n$ of the group’s members because we assumed the LKH tree balanced. As
a matter of fact, in case of group of type G3 or G4, it involves at most $O(h)$
symmetric encryption operation (which cost $h \cdot E_{sk}$), for the keys along the path
from the root of the key tree to the leaf representing the joining user, plus one
asymmetric encryption operation (which costs $E_{AS}$) concerning the individual
symmetric key to be sent to the new user. For group type G2, since the keys
on the path from the root of the key tree to the leaf of the joining user are
updated, they must be distributed to both the old members of the groups and
the joining user, by encrypting them with different keys. As a result, at most
$O(h)$ keys on the path must be encrypted twice with respect the join on group
G3, or G4. Instead, the cost introduced by the leave operation on group G2
and G4 depends on both the height $h$ of the key tree and the maximum number
of children nodes $d$ (which is constant), because each new key on the path from
the root of the key tree to the removed leaf must be symmetrically encrypted
with the keys on the $d$ children nodes. Such cost, which is at most equal to
$O(d \cdot h \cdot E_{sk})$, is also present in the case of leave on groups of type G3, where the
contents already published in the group must be re-encrypted, thus introducing
an additional cost of $O(p \cdot E_{sc})$ for the encryption of the contents and $O(p \cdot E_{sk})$
for the encryption of the new contents keys. Finally, the cost for the publication
of a content is the same as for the Encryption-based model.

The cost of the Allocation-based enforcement model in the case of join on
group G2 is equal to the cost of adding the user to the member list of the
group, i.e., $O(z)$, while in the case of leave on group G2, and G4, the cost of
removing the user from the member list is equal to $O(w)$. Instead, in the case
of join on group G3 and G4, as well as in the case of the leave on group G3,
the current members list must be updated by adding or removing the involved
user. In addition, the privacy policies on the contents $p$ already published in the
group must properly modified in such a way that the user added to the group
can access the contents already published in the group, and the user removed
from the group cannot access such contents anymore. Finally, in the case of
publication of a contents, the cost depends on the complexity of the privacy
policy of the group which, in turn, depends on the number of current members
of the group, $n$.

In order to numerically compare the 3 enforcement models in a realistic
scenario, a graphical and more intuitive representation of such costs is given by
the plot in Figure [4], where we measured the time taken by the enforcement
models to perform the operations on different types of groups. In particular,
we identified three different categories of groups based on both the number of group’s members \( n \) and the number of contents \( p \) published on the groups: passive, normal, and active groups. Passive groups category consists of groups with low level of activity where the number of contents \( p \) published by groups members is less than the number of members in the group (i.e., \( p << n \)) while in normal groups category the number of contents \( p \) published by group’s members is more or less the same as the number of members \( n \) (i.e., \( p \simeq n \)) and it represent groups with a balance level of activity among members. Finally, active groups category consists of groups with a high level of activity where the number of contents \( p \) published on the group is higher than the number of group’s members (i.e., \( p >> n \)). We derive the average number of groups’ members from [28], where the size of 18 real Facebook groups of different types has been monitored and analyzed over time. Based on the results of [28], we assume that each group consists of about \( n = 4000 \) members. Consequently, for what concerns the number of posts published in the group, we suppose: i) \( p = 2000 \) contents in the case of passive groups, ii) \( p = 4000 \) contents in the case of normal groups, and \( p = 8000 \) contents in the case of active groups. Furthermore, we set the maximum number of children nodes \( d \) of the key tree to \( 4 \). We performed the experiments using the same test platform we exploited for the experiments we described in Section 5. To ease the plot reading, the performance results obtained by each group are normalized by using the min-max normalization, and the cost axes report three values: low (close to the heptagon center), medium, and high (in the heptagon borders), which correspond to increasing amounts of time.

The three plots clearly indicate that, for the group join operation, the three enforcement models expose a similar cost, while for the group leave operation the three models expose different performance which must be evaluated on a case-by-case basis, depending on the type of group. For instance, in case of groups of type G2, the cost of the join operation in the Encryption-based and in the LKH-based models is about 0.16 ms. As a matter of fact, the additional cost introduced by the LKH-based enforcement model with respect to the Encryption-based one due to the management of the key tree is negligible in our experiments (where \( n = 4000 \)) with respect to the cost of Asymmetric Encryption. The Allocation-based model, instead, takes 0.10 ms (see Figure 10(a)). Also in the case of groups of type G3 and G4, the cost of the join operation in the Encryption-based and LKH-based models is mainly due to the Asymmetric Encryption, thus resulting to be 0.16 ms in both cases, while in the Allocation-based model the cost is 3.2 ms for groups of \( p = 2000 \) contents and 10.8 ms for groups of \( p = 8000 \).

The execution of the group leave operation on groups of type G2 and G4 when the Encryption-based approach is adopted takes about 640 ms, because of the number \( n = 4000 \) of Asymmetric Encryption operations, while the same operation executed on groups of type G3 requires also the re-encryption of the contents already published in the group, i.e., about 4221 ms in the case of group with \( p = 8000 \) contents.

In the case of the LKH-based approach, the leave operation on groups of type G2
Figure 14: Comparison of the execution time of the join, leave and publish operations in the three enforcement models.
and G4 takes only 0.006 ms, because it requires a limited number of symmetric encryption operations, while the leave operation on group G3 requires also the re-encryption of the contents already published in the group, i.e., about 3581 ms in the case of group with $p = 8000$ contents. The execution of the group leave operation adopting the Allocation-based approach on group G2 and G4 takes about 0.1 ms, because it only needs to remove a member from member list, while the leave operation on groups of type G3 requires also the modification of the privacy rule paired to each published content. As a result, the cost depends on the number of contents on the group and it ranges between 3.29 ms for group with $p = 2000$ contents and 10.8 ms for group with $p = 8000$ contents.

Summarizing, in the three plots shown in Figure 14, the normalized cost of the group join operation results to be low for any type of group, for any enforcement model, and for any category of group. In the case of leave operation, regardless of the group type, the plots clearly show that, in our experiments, the Encryption-based enforcement model introduces the highest cost. As a matter of fact, in case of groups of type G3 the normalized cost results to be high for the three group categories and it is dominated by the time taken for re-encrypting all the contents of the group. Instead, in case of groups of type G2 and G4, the normalized cost results to be close to medium for passive groups and in between medium and low in case of normal and active groups. Instead, the LKH-based and the Allocation-based enforcement models are alternative solutions providing lightweight implementations of the leave operation. In particular, under the assumptions on the values of $n$ and $p$ we made, the normalized cost of the leave operation in the Allocation-based enforcement model always results to be low, while the normalized cost of the LKH-based model results to be low for the three group categories only for groups of type G2 and G4. Instead, for groups of type G3, the normalized cost of the leave operation in the LKH-based model results to be medium in case of passive groups, and between medium and high in case of normal and active groups. Such costs reflect the number of contents in each group because it is necessary to re-encrypt again all of them. As a result, the Encryption-based enforcement model is well suited to manage groups where either the leave operation is not permitted or it does not often occur, because the leave operation is very expensive.

In the case of the publication of a content, the Allocation-based, the LKH-based, and the Encryption-based enforcement model introduce a similar overhead. However, one of the main differences between the Allocation-based and the LKH-based or the Encryption-based models is that in the former the contents of users are stored and maintained according to the users’ privacy preferences while in the last ones models the contents of users can be stored on any peers of the DOSN because they are encrypted only for authorized members.

Finally, another important aspect of the proposed models is the availability of protected contents. The contents protected using both the Encryption-based and the LKH-based enforcement models can be stored and replicated on any peers of the system because they are encrypted with a shared asymmetric key known only to authorized members. Instead, the Allocation-based enforce-
ment model can store the contents only on some trusted peers of the system and the availability of such contents depends on the peers selected as replica. As a result, Allocation-based enforcement could not ensure the availability of the contents and it introduces a further hidden cost for managing replica’s peers.

7. Future directions

In the following, we draw future research directions related to privacy enforcement models in DOSNs and, based on the previous comparison, we also identify some open issues related to the privacy enforcement models which deserve further investigation.

7.1. Open issues

Current researches focus their attention on the following major challenges:

How to reduce the computational cost when a leave occurs? The reasons for a user to leave (or to be removed from) a group can be different (e.g., the member is not interested in the topic discussed in the group anymore, or the member behaves improperly) and the group membership revocation must be securely and efficiently implemented by any privacy enforcement model. However, achieving a low computational cost for group membership revocation remains a relevant challenge because of the high number of members typically involved in groups. A recent approach used to mitigate this problem is to design privacy enforcement models that define some order relationships among either the members of a group or the members of different subgroups, making constant the computing overhead required to remove a member from a group in the best case scenario. However, such approach exposes an high computational overhead in the worst case scenarios, and rely on the fact that such scenarios are unlikely to happen [87].

How to enhance the security level of privacy enforcement models? Since some privacy enforcement models rely on encryption algorithms, cryptographic key management, digital signatures, and hashing functions, then the reliability and security of such models heavily depend on such algorithms and their configuration parameters. For the introduced reasons, privacy enforcement models used in current DOSNs must follow security recommendations provided by IT advisors, government organizations, or cybersecurity agencies about the cryptographic keys size and the algorithms to be used. For instance, the National Institute of Standards and Technology (NIST) develops cybersecurity standards and encourages the adoption of guidelines, best practices, and other recommendations that help system administrators and users to secure their data and applications. However, our analysis reveals that most of the existing DOSNs provide groups with public membership information, i.e., they do not hide the identity of the group members to the other users of the DOSN. In particular, the most part of
current DOSNs do not support groups having protected or private membership because the group membership information is disclosed through key management and interactions between members. To address the above issue, privacy enforcement models proposed by current DOSNs could adopt onion routing [41] and anonymization techniques to provide mitigation against identity disclosure [20].

How to dynamically adapt the characteristics of privacy enforcement models to the user’s needs? Users connect to OSNs by using several devices with different characteristics, some of them having limited computational and storage capacity. Consequently, adaptive privacy enforcement models are necessary to deal with heterogeneity of users devices, demands, and usage behaviour. For instance, the pervasive penetration of mobile devices (such as smartphones and tablet) has changed the ways in which people connect to the DOSNs [88] and introduced several challenges, such as finding privacy enforcement models with limited computational and memory resources requirements. Indeed, due to technical constraints, some mobile devices cannot support the use of specific cryptography operations and/or are not able to store the whole cryptographic material needed by the privacy enforcement models [23]. Additionally, users can configure the DOSN to be executed on different devices having either pay-as-you-go resource management model (e.g., virtual machine provided by cloud storage provide) or pre-paid resource management model (e.g., mobile devices with a limited plan for data download). Consequently, users have to pay for resources used by the DOSNs. In such a case, in particular in the Allocation-based enforcement model where the allocation strategy is driven by the privacy preferences expressed by the content publisher, a malicious publisher can exhaust the resources of other users by sharing a massive number of contents with them. To prevent this from happening, the privacy enforcement models should prevent denial of service attacks by introducing context-aware adaptation strategies that monitoring consumed resources [89].

How to support the collaborative administration of groups? Large groups can have a very complex internal structure consisting of several members who have different roles and collaborate with each other for managing groups’ activities. Our analysis reveals that privacy enforcement models having collaborative administration policy are not supported by current systems (see Table 2), hence they need to be integrated within current DOSNs. Indeed, the administration of a group is an important characteristic of the privacy enforcement model because it regulates who can authorize or really initiate the execution of the user join or leave operation. In addition, in the case of a group with collaborative administration, the sequence of operations generated by the administrators could raise some conflicts and new recovery mechanisms must be designed to keep the group information updated and to resolve inconsistency [90]. For instance, multimedia contents produced in OSNs, such as photos or videos, can have multiple owners (e.g., several users may appear in the same picture [91]) and each of them may want to
define a different access policies for the shared item. Collaborative access control models [92] were proposed to enable security policy definition [83], negotiations [94], and conflicts resolution [90] in a collaborative way. Unfortunately, existing collaborative access control models have been designed to support few application scenarios (e.g., healthcare) and they do not consider the requirements of DOSNs’ users.

7.2. Blockchain-based privacy enforcement model

Recently, Distributed Ledger Technology (DLT) [95] has gained considerable attention from industry and academia due to its applicability in several relevant scenarios. The blockchain is one of the most popular type of DLT, allowing to establish trust in an open and decentralized environment while providing a rich set of tools that cover various tasks (e.g., smart contract and token). Several works have been proposed in the literature exploiting blockchain to enhance the privacy of contents published by DOSNs’ users. However, some characteristics of the blockchain (e.g., immutability) could conflict with some privacy regulations (such as the General Data Protection Regulation which requires that users can delete all personal information [96]) and further studies are needed to understand which privacy requirements can be accommodated by the privacy enforcement models implemented in DOSNs [97].

With regard to content privacy, most of the existing DOSNs use the blockchain as an infrastructure to verify the correctness of the published contents. For instance, the DOSNs proposed in [51, 98] leverage blockchain to ensure the integrity of the contents stored on a distributed storage service based on DHT [99]. Indeed, the blockchain is used to store an hash of each content, while users can use the hash values stored in the blockchain to query the corresponding data on the DHT. A similar approach is recommended in [100], where InterPlanetary File System (IPFS) [149] is used as distributed data storage service while the blockchain is used to verify the integrity of the contents.

In contrast to the previous approaches which store on the blockchain only an hash pointer, some DOSNs prefer to store the original contents on the blockchain. For instance, Steemit [7], Hive [8], Sapien [9] and SocialX [10] utilize blockchain to store textual contents and to regulate compensation of users for their actions (such as, creating a content or reviewing an item). Since contents are stored on the blockchain, each user can retrieve and verify them [46, 51, 98]. However, privacy enforcement models are not considered in these platforms because anyone can see all contents without restrictions.

Authors of [46] proposed a solution to ensure the correctness of contents published in the DOSN by focusing on the scalability issues introduced by blockchain [101]. The original content is stored unencrypted on several peers of the DOSNs.

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6 Available at: https://ipfs.io
7 Steemit: https://steemit.com/
8 Hive: https://hive.io/
9 Sapien: https://www.sapien.network/
10 SocialX: https://socialx.network/
while the hash of each content is recorded on a shard, i.e., a parallel blockchain which records transactions relevant to the content owner. Since many shards exist in the DOSNs, the state of each shard is hashed and recorded in the blocks of the main chain by using Verifiable Random Functions \cite{102}.

Blockchain technology can be used to protect access to users’ contents while ensuring the quality of the services. In particular, DOSNs can exploit Proof-of-Work (PoW) to prevent the storage service from Denial-of-Service (DoS) attacks resulting from large amounts of requests sent, preventing overload of requests. For example, in \cite{40} the user requesting a content has to solve a PoW, whose complexity depends on both the load of the network and the users’ request rate, and it acts as a stamp used to pay for the delivery of requests.

Another interesting approach to protect access to users’ contents is to employ the blockchain as a medium to distribute cryptographic keys, tokens, or policies between friends. In particular, the cryptographic keys or tokens must be securely stored on the blockchain, and they can be retrieved by authorized users in order to decrypt contents stored on the storage layer. For instance, in \cite{51, 103, 104, 105} the contents are encrypted by using secret key and stored on a third-party storage provider while the blockchain contains the secret key encrypted with the asymmetric public keys of the users authorized to access such contents. Instead, some approaches \cite{106, 107} store an identifier of the encrypted content on the blockchain along with a token which is used to monitor the propagation of information and to limit the number of re-shares that can be performed with that content. Whenever a user re-shares the content, she/he makes another transaction which is registered on the blockchain only if the token value is greater than 0.

As per privacy policies, they are stored on the blockchain with the aim of being enforced by an external access control system. For instance, the blockchain can provide users with the ability to define ACL that can be evaluated by the storage system \cite{108}, while in \cite{109} the blockchain is in charge of storing both the privacy preferences of a user in order to determine whether the privacy settings assigned by the social network are compliant with those declared by the user.

8. Conclusion

In this paper we analysed the enforcement models used in current Decentralized Online Social Networks (DOSNs) to assess the provided level of protection of the contents that are published in social groups. In order to analyse such models, we evaluated for each of them the cost of executing the three typical operations of a DOSN (i.e., group join, group leave and content publish), on different types of groups.

The obtained results reveal that the Encryption-based enforcement model is affected by a serious drawback: it is not scalable because the number of asymmetric encryption operations to be executed to remove a user from a group is linear with the number of users belonging to that group, and this could cause a relevant overhead in case of large groups. We showed that the LKH-based enforcement model can solve the above issue by exploiting the Logical Key Hier-
archy model in order to optimize the costs of the operations (i.e., dramatically reducing the cost of the group leave operation while slightly increasing the one of the group join operation) thus enabling dynamic groups management. However, the LKH-based enforcement model behaves like the Encryption-based model when the groups are quite static because they both require to encrypt the contents with a symmetric schema.

The Allocation-based enforcement model is an alternative approach that can be used to solve the cited problem because it is not based on content encryption. This approach allows users to define privacy policies on their contents by using a privacy policy language and the allocation of users’ contents is performed on the basis of the privacy policy defined by the content owner. However, the Allocation-based enforcement model introduces some overhead required for privacy policy definition and evaluation (which depends on the complexity of the policies). In addition, in order to ensure high availability of the published contents, this approach also needs to consider the availability patterns (online/offline) of the users, in order to allocate the contents on the peers that will probably be online for more time.

The above findings are supported by a thorough analysis and extensive experimental campaigns. Finally, research directions on how to tackle the highlighted problems and further open issues in DOSNs are also provided.

Acknowledgements

This publication was partially supported by awards NPRP-S-11-0109-180242 from the QNRF-Qatar National Research Fund, a member of The Qatar Foundation. The findings are solely responsibility of the authors.

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