

Vulnerability Disclosure or Notification? Best Practices for Reaching Stakeholders at Scale

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Security researchers are interested in security vulnerabilities, but these security vulnerabilities create risks for stakeholders. Coordinated Vulnerability Disclosure has been an accepted best practice for many years in disclosing newly discovered vulnerabilities. This practice has mostly worked, but it can become challenging when there are many different parties involved.

There has also been research into known vulnerabilities, using datasets or active scans to discover how many machines are still vulnerable. The ethical guidelines suggest that researchers also make an effort to notify the owners of these machines. We posit that this differs from vulnerability disclosure, but rather the practice of vulnerability notification. This practice has some similarities with vulnerability disclosure but should be distinguished from it, providing other challenges and requiring a different approach.

Based on our earlier disclosure experience and on prior work documenting their disclosure and notification operations, we provide a meta-review on vulnerability disclosure and notification to observe the shifts in strategies in recent years. We assess how researchers initiated their messaging and examine the outcomes. We then compile the best practices for the existing disclosure guidelines and for notification operations.

CCS Concepts: • Security and privacy → Vulnerability management.

Additional Key Words and Phrases: Vulnerability Disclosure, Vulnerability Notification, Best Practice

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1 Introduction

Coordinated Vulnerability Disclosure (CVD), formerly known as responsible disclosure, is a best practice in the security community for dealing with discovered vulnerabilities. When a new vulnerability is found, the finder conducts a risk and impact assessment and then initiates conversations with stakeholders to mitigate vulnerable systems or services in time. However, due to the shift in the network landscape, the scale of vulnerable systems and stakeholders involved has changed drastically from the past [10, 31]. The amount and variety of vulnerabilities have increased [20], and so have the affected parties [6, 15]. This brings a new challenge for security researchers: figuring out a scalable method to identify reliable contact information and ensure the message is delivered to the stakeholders.

Despite the challenges in vulnerability disclosure, notifications to stakeholders with known vulnerabilities that remain in existing systems have gained attention over the years [31]. We identify the practice as vulnerability notification that informs end-users, such as domain owners, hosting providers, network operators, and incident responders. These stakeholders are different from vendors, who are traditionally the stakeholders in CVD. Whether or not the vulnerability is possibly known to the stakeholders and the public is the difference between vulnerability disclosure and vulnerability notification. A finder discovers a new vulnerability and plans to disclose it to the vendor in vulnerability disclosure, while a finder locates a known vulnerability on existing machines and notifies the end-users in vulnerability notification.

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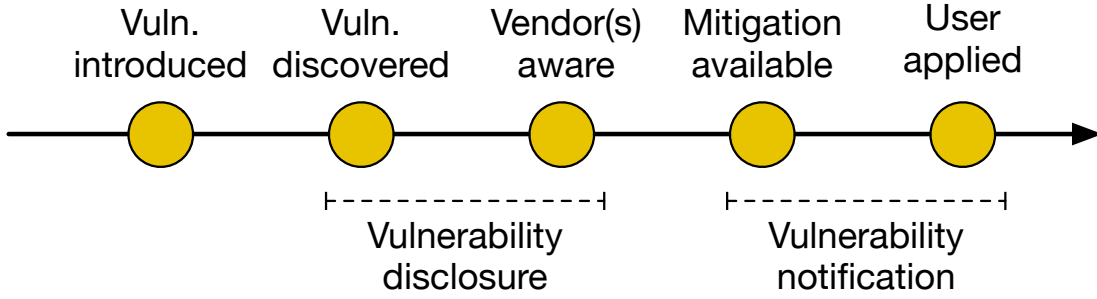


Fig. 1. Vulnerability Disclosure and Notification

This means that vulnerability notification is often conducted after the vulnerability disclosure. In particular, after a newly found vulnerability has been disclosed and mitigated with stakeholders or even made public, it is not guaranteed that all vulnerable systems are treated on a timely basis [10]. Hence, vulnerability notification is there to improve the safety of the internet.

Vulnerability notification is initiated after network scanning [30] or vulnerability analysis on existing datasets [9] to locate the vulnerable systems with targeted vulnerabilities. A finder should retrieve the stakeholders' contact information and select a communication channel to reach the affected parties. However, similar to the challenge in vulnerability disclosure, notification to stakeholders also suffers from the high number and complexity of stakeholders [24, 40]. The contact retrieval and notification at scale pose an even tougher challenge to finders [16, 26] since stakeholders have a higher tendency to have multiple parties involved [9, 40]. Moreover, unlike vulnerability disclosure with CVD as the best practice, best practices for vulnerability notification at scale are still lacking in the community.

2 Background and Related Work

2.1 Vulnerability Disclosure and Notification

Vulnerability disclosure, especially coordinated vulnerability disclosure, has been an accepted practice in security research for years. There have been numerous publications and even standards published on this process [2]. However, notifying users with vulnerable systems has usually not been seen as a separate practice, but can come with challenges of its own. The difference between the two processes is illustrated in Figure 1.

In *vulnerability disclosure*, a finder discovers a new vulnerability and aims to share this with the vendor. The role of the finder in the following content includes both the responsibilities of identifying a vulnerability and informing the responsible parties [12]. Once the disclosure process has started, the vulnerability will usually be revealed for the first time. The finder and vendor(s) discuss the finding with or without a coordinator's support. Subsequently, the vendor works on a mitigation. Vulnerability disclosure needs trusted channels and message details to minimise disclosure leaks to unwanted receivers. The finder may also need to expect extra steps to communicate with the stakeholder on whether or not and how to disclose the new vulnerabilities to the public, based on the disclosure policy and legal agreement on both ends. After some time, the vulnerability is made public, usually with a possible mitigation available.

In *vulnerability notification*, the vulnerability information is already available to the stakeholders before a notification starts. This means the vulnerability has already been documented and revealed to the stakeholders or the public. The weakness is likely documented with CVE numbers or discussed within specific communities. Potential malicious parties,

such as criminals, may also know the existence of the vulnerabilities and can try to abuse them. The receiving users may or may not be aware of the existence of the vulnerability before seeing the notification message. Once they are aware of the issues, they may be able to find the vulnerability information with resources that are not limited to the finder. This can lead to different user response behaviours to the finder. The affected user may also have a different risk assessment based on the severity of the vulnerabilities. The aim of the notification process is to improve general security by removing vulnerable systems.

We note that there are many overlapping challenges in vulnerability disclosure and notification, such as formulating the initial message, choosing the communication channel, and dealing with responses. However, due to the nature of the different stakeholders involved and especially the difference in scale, the challenges are fundamentally different.

2.2 Evaluations of Disclosure and Notification

Vulnerability disclosure has received best practices over the years through the contributions from security researchers, vendors, and support organisations. There have been several publications describing the practices in detail and examining their effectiveness. Householder et al. [14] proposed a model to assess the coordinator role in CVD, which provides insight into incident handling of vendors and the vulnerability lifecycle. Walshe et al. [37] examined the effectiveness of how vendors with CVD programs and outsourced vulnerability platforms receive and process vulnerability disclosure. They revealed that disclosure program operators face a large number of vulnerability reports, which becomes a burden in vulnerability prioritisation. Nakajima et al. [20] looked into vulnerability management of IoT vendors across two countries and pointed out the disclosure pitfalls to avoid.

Vulnerability notification has received growing attention over the last decade, especially in the review of the notification efficiency. The Dutch Institute for Vulnerability Disclosure (DIVD) proposed the notification guideline [31] based on their framework and the Communication-Human Information Processing (C-HIP) model [38] with their notification operation experiences. Their contribution focuses on scalable notification strategies for end-users, such as an incident responder and an abuse specialist. Additionally, the challenges they documented with end-users resemble the capacity and awareness issues of program operators discussed in [37].

Evaluations of vulnerability disclosure and notification at scale still require attention despite contributions trying to address the challenges from different aspects over the years. An extensive assessment and best practices for performing disclosure, especially notification at scale, are needed. There has been research focusing on finders trying to reach out to other stakeholders effectively and documenting the complete process of their disclosure and notification operations. The work will be discussed in the following sections with our assessment and comparison with best practices suggested by the communities and support organisations.

2.3 Large-Scale Disclosure and Notification

Large-scale disclosure operations have been constantly reported as an increasing challenge by studies in the recent decade [6, 14, 19, 20, 31, 32, 37]. Unlike the one-to-one or one-to-multiple disclosure to vendors, the complexity and amount of stakeholders to inform have increased to a level beyond the effort individuals and small teams can make.

Many of the challenges associated with multi-party disclosure processes have been identified by CERT/CC [8] and the FIRST Special Interest Group on Vulnerability Coordination, resulting in a best practice document "Guidelines and practices for Multi-Party Vulnerability Coordination and Disclosure"[12]. These best practices support the challenges of disclosing newly discovered vulnerabilities and, through different scenarios, describe the challenges and impacts for various stakeholders, i.e. finder, vendor, defenders and users. The VINCE platform [7] has been developed by CERT/CC

and others to support multi-party disclosures and prevent many of the possible mistakes identified in the best-practice guide.

Moreover, many countries have introduced laws and regulations to stimulate stakeholders, with support from national CSIRTs, professional organisations, and others, all supporting the practice of vulnerability disclosure [2, 12, 21]. Research institutes, universities, and companies such as Google and Facebook have adopted outgoing disclosure policies to protect the finders and make their intentions clear to receiving parties. [22, 31].

A vulnerability disclosure to multiple parties is considered to be large-scale when there are five or more vendors involved and can become very complicated and stressful [6, 19, 32]. However, vulnerability *notification* processes can quickly become large-scale, and the affected parties can be counted in the hundreds or even thousands. Identifying the contact information and notifying the responsible parties behind the vulnerable systems can be overwhelming for finders [16, 24, 25, 40], which can eventually limit the development of vulnerability notification.

There have been contributions to improve the efficiency of the notification mechanism. Emails have been empirically confirmed as the method of reaching large numbers of affected parties despite the drawback of low delivery rate and inaccurate contact information [25, 26, 31, 40].

Nonetheless, the current disclosure best practices are still struggling to catch up with the growing nature and importance of digital infrastructure. With best practices and prior experiences as a foundation for large-scale disclosure, the recent effort still suffers from the slow adoption of disclosure policy and incident handling among stakeholders. There are increasing large-scale internet-wide notification cases beyond the support of local or national security centres, which lead to finders having to carry out the notifications by setting up a messaging infrastructure themselves [9, 24]. It has been reported that contact identification remains challenging, and the notification operation is still not broadly accepted among stakeholders [9, 19]. This shows that large-scale notification still requires new proposals to improve the process for both the notifying and receiving parties.

3 Problem Statement

How to disclose a vulnerability to a vendor is already well-considered, with CVD as the best practice, both for researchers [28], as well as governments and vendors [2]. Over the last few years, more and more support mechanisms have come into place to support multi-party or even large-scale vulnerability disclosure. Still, it is unclear how well these are known in the academic security research community.

As we noted above, a large-scale vulnerability notification operation differs from disclosure and requires contacting other stakeholders differently. Publications often mention that it is challenging for security researchers, practitioners, and ethical hackers to reach out to the stakeholders in time. We examine the differences between disclosure and notification and examine the challenges associated with large-scale disclosure and notification operations.

From the above, we gather experiences from literature, community, and support organisations to propose best practices for the academic community to perform vulnerability disclosure and notification in the most efficient and effective way.

4 Literature Selection

We collected publications with extensive documentation on large-scale vulnerability disclosure or notification operations in the recent decade. We used literature search engines to find publications initially and performed a selection depending on the inclusion of disclosure procedures in stages and documentation before and after the disclosure or notification operations. We did not exhaustively locate all available disclosure or notification work. Rather, we selected work that can

be representative of the large-scale disclosure and notification implementation in different disclosure and notification scenarios.

The initial search patterns we used were the combination of "vulnerability", "disclosure", "notification", "large-scale", and "network" to look for the publications through major academic security conferences, literature databases, and search engines such as ACM Digital Library, IEEE Xplore, Scopus, and Google Scholar with all fields or metadata search filter enabled. We skimmed through the title, abstract, and partial content of search results that fit into the large-scale disclosure or notification scenarios discussed in Section 2.3. The initial result was broad and diverse. After a few iterations, we narrowed down our search keywords to "vulnerability disclosure" and "vulnerability notification", with synonyms such as "vulnerability alert" and "vulnerability warning". This gave us a short list of approximately 60 results that were relevant to vulnerability disclosure and notification.

To finalise the short list of publications, we examined the literature candidates with details such as assessment before an operation, selection of communication channels and messaging infrastructure, review after the operations, and contribution to best practices. We assigned different categories based on communication channels and involved stakeholders to seek the differences and choose work that has a measurable impact on the community. Furthermore, to understand the development of disclosure and notification best practices over the years, we aimed for publications that can be used to compare with each other, such as adopting, changing or improving methods based on other selected work. This means we looked into the reference list and related work sections of the publications to seek correlations and influences. Besides, we also selected work that made an impact in the cybersecurity community to illustrate the CVD as best practice in the last decade and to stimulate the discussion on how we can improve the existing guidelines. Finally, we separated the publications into vulnerability disclosure and notification operations as mentioned in Section 2.1.

As a result, we selected 15 distinct publications that well represent large-scale vulnerability disclosure and notification using several approaches in different scenarios from the last decade. We separate the work into two tables in chronological order. Table 1 presents the vulnerability disclosure operations, whereas Table 2 presents the vulnerability notification operations. To comprehend the selected work, we develop assessment stages to look into each disclosure or notification operation in the following subsection.

4.1 Stages of Operation

In the literature selection, we cross-reviewed each selected work in detail and aimed to figure out the common procedure for performing vulnerability disclosure and notification. Eventually, we compiled five stages to represent the procedure implemented across the literature. We then use the stages to extract key points, numbers, and remarks from the selected work to better understand efforts, considerations and reviews made in the operations. This results in the following stages to assess the selected publications:

Pre-Assessment – Before a vulnerability disclosure or notification can start, a finder will assess the risk and impact of the discovered vulnerability. We identify the type and number of involved stakeholders and the vulnerabilities, and extract the impact scale of the vulnerability to understand the preparation before an operation.

Communication Channel – After deciding on the stakeholders to inform, the proper communication channels should be selected to deliver the messages. We list the single to multiple communication channels used in each operation to inform the affected parties.

Messaging Infrastructure – For the message to be delivered with the selected channel, the right messaging infrastructure should be used to ensure message delivery. We distinguish the messaging infrastructure used by finders to deliver the message, as well as the infrastructure used by the stakeholders to receive and forward the message.

Title	Year	Pre-Assessment	Post-Review
Key Reinstallation Attacks: Forcing Nonce Reuse in WPA2 [34]	2017	To Wi-Fi related vendors, Key reinstallation attacks, At least 6 vendors	Increased to 84 vendors (VINCE), Measurement and notification delegated to CERT/CC and vendors
Talking Trojan: Analysing an Industry-Wide Disclosure [6]	2022	To software vendors, Trojan Source, 13 vendors	Increased to 19 vendors (VINCE), Measurement delegated to vendors, GitHub, and Rust team
rpkiller: Threat Analysis of the BGP Resource Public Key Infrastructure [32]	2023	To software vendors, RPKI implementations, 8+ software vendors	5 vendors released fixes, 2 vendors didn't release the fix, 1 vendor stopped support
Vulnerability Disclosure Considered Stressful [19]	2023	To vendors, network operators TsuNAME (DNS resolver&clients), 5+ vendors, operator communities	Measurement not specified, 1 DNS community meeting, 3 security events
Haunted by Legacy: Discovering and Exploiting Vulnerable Tunnelling Hosts [4]	2025	To vendors, domain owners, Tunnelling protocol & EDoS, 3,527,565 IPv4, 735,628 IPv6 hosts	Up to 14 domains directly notified, Measurement & notification delegated to CSIRTs and Shadowserver

Table 1. Vulnerability Disclosure Operations

Disclosure Policy and Message – The wording of the message should be tuned to the stakeholders to ensure comprehension and follow the needs of the recipients. We reflect on how the finders composed their message and handled the conversations with other stakeholders. In addition, we also check on disclosure policies used by the finders and other stakeholders, if presented.

Post-Review – An operation can be reviewed by tracking the remediation rate, feedback of stakeholders, and experiences in each stage. A finder can also reflect on the operation and contribute to best practices. We extract the notified hosts and domains, remediation rates, interactions between the stakeholders, and contribution to best practices of large-scale disclosure and notification operations.

To present the overview of the assessment of each publication, we arrange three tables based on the above 5 stages. Tables 1 and 2 both contain the publication titles, pre-assessment, and post-review to indicate the efforts and outcomes from each work with different scenarios considered. Table 3 shows the single or multiple communication channels and messaging infrastructure implemented in each reviewed disclosure or notification operation.

5 Lessons Learned

This section presents the insights we have gained from the selected work on large-scale vulnerability disclosure and notification. We also integrate the experience we learn from the community, support organisations, existing guidelines and standards to present the essence of the disclosure or notification procedure.

With Table 1, 2, and 3 presented as an overview of disclosure and notification operations, we first discuss the development of best practices from the experiences of the selected work in Section 5.1. Then, we compare how the finders adopted the past best practices and what they learned from their operations in Section 5.2.

5.1 The Development of Best Practices

Security researchers, practitioners, communities, and support organisations have been seeking optimal methods and strategies based on the disclosure and notification best practices presented in their time, as shown in Table 1 and 2. We

Title	Year	Pre-Assessment	Post-Review
The Matter of Heartbleed [10]	2014	To network operators, TLS Heartbeat Extension, 588,686 vulnerable hosts	212,805 hosts notified, 4,648 emails (WHOIS), 57% mitigated
You've Got Vulnerability: Exploring Effective Vulnerability Notifications [15]	2016	To network operators, 45,770 ICS, 83,846 DDoS Ampl., 180,611 IPv6 Firewall hosts	79.7% ICS, 92.4% Ampl., 99.8% IPv6 notified, 9,918 emails (WHOIS), Up to 18% mitigated
Hey, You Have a Problem: On the Feasibility of Large-Scale Web Vul- nerability Notification [26]	2016	To website owners WordPress(WP) & Client-Side XSS, 44,790 vulnerable domains	35,832 domains notified, 17,819 emails (alias, WHOIS), 25.8% WP, 12.6% CXSS mitigated
Make Notifications Great Again: Learning How to Notify in the Age of Large-Scale Vulnerability Scanning[40]	2017	To nameserver/network operators, DNS Dynamic Updates, 21,506 vulnerable domains	4,149 nameserver IPs notified, 5051 emails (WHOIS), Up to 20% mitigated
Didn't You Hear Me? - Towards More Successful Web Vul- nerability Notifications [25]	2018	To website owners, WordPress(WP) & Git, 24,000+ vulnerable domains	20,602 domains notified, 103,819 emails (alias, WHOIS), 17% WP, 24% Git mitigated
Tell Me You Fixed It: Evaluat- ing Vulnerability Notifications via Quarantine Networks [39]	2019	To ISP retail customers, DNS resolvers & mDNS services, 1688 retail customers	688 customers notified, 86.6% walled garden only, 75.1% email only mitigated
User Compliance and Remediation Success after IoT Malware Notifi- cations [23]	2021	To ISP retail customers, IoT Malware (Mirai Family), 177 retail customers	From 50 responded participants, 95% walled garden, 82% email only started mitigation
Effective Notification Campaigns on the Web: A Matter of Trust, Framing, and Support [16]	2021	To website owners, IP Anonymization Misconfigured, 7979 non-compliant sites	4594 owners of 4754 sites notified, 2660 letters, 1,337 emails (Manual), 76.3% letter, 33.9% email mitigated
Uncovering the Role of Support In- frastructure in Clickbait PDF Cam- paigns [24]	2024	To website owners, Clickbait PDF, 177,835 vulnerable hosts	8,842 domains notified, 1,522 emails (alias, WHOIS), 29.567% mitigated
Are You Sure You Want To Do Coordinated Vulnerability Disclo- sure? [9]	2024	To IoT backend operators, MQTT & Misconfigured Backends, 15,820 vulnerable backends	15046 backends notified, 2,132 emails (WHOIS), 2.25% mitigated

Table 2. Vulnerability Notification Operations

have seen changes in their selection of communication channels, messaging infrastructure, contact retrieval, message formulation, and disclosure policies depending on the nature of the found vulnerabilities, notification scalability, and recommendations from the communities.

The essential part of vulnerability disclosure and notification is ensuring messages reach the responsible parties and prompt them to action. As presented in Table 3, the finders used different communication channels and messaging infrastructure to ensure the delivery of the disclosure messages, either on their own or with support organisations, such as national CSIRTs and Shadowserver Foundation. To maximise the notification coverage, all work adopted more than a single communication channel, and most of them delegated notifications to support organisations.

Shadowserver Foundation is a non-profit organisation founded in 2004, driven by the vision of a secure, threat-free internet. They do this by scanning the internet for known vulnerabilities and performing notifications, managing sinkholes for malware command-and-control infrastructure, and operating honeypots and honeyclients to monitor

threat developments. Over the years, the team at Shadowserver Foundation has created a large, trusted network with national CSIRTs, ISPs and others to ensure that they are able to reach as many stakeholders as possible. Anyone can sign up to get threat reports about their domain or IP as long as they can prove ownership. More importantly, Shadowserver Foundation can support researchers in performing notifications to stakeholders, as described by Beitis et al. [4, 27].

The earlier vulnerability notification operations in [10, 15] focused on email and coordinator delegation notifications, then others in [25, 26, 40] extensively implemented diverse communication channels, compared the effectiveness of each empirically, and provided valuable suggestions to best practices on large-scale notifications. These operations served as the foundation for the large-scale notification best practices.

The later operations in [9, 24] adopted best practices from the prior work. They narrowed down the channel selection and dived into the experiences with email notifications. On the contrary, Maaß et al. [16] decided to explore alternatives other than the best practices with costly manual efforts on email, post, and phone call. All their results reflected the prior best practices and helped improve notification best practices at scale. In all the above work, locating accurate contact information remains the major challenge regardless of the selected communication channels. On the other hand, the researchers [23, 39] cooperated with a medium-sized ISP to explore the effectiveness of email and specialised ISP notification systems with different vulnerabilities, which serves as an example in notification with direct intervention from an ISP to their customers.

Furthermore, vulnerability disclosure to vendors has received promising best practices as implemented in [6, 32–34]. Boucher et al. [6] have provided well-structured details on acquiring CVEs, CERT/CC VINCE notification, public press disclosure, and constraints in academic publication. However, despite the adoption of best practices, the researchers in the two disclosure operations [32–34] tackled different software vulnerabilities but encountered the challenge of inviting the same stakeholder to participate in CVD. Last but not least, the two operations [4, 19] cover both vulnerability disclosure and notification. Their experiences revealed the long-lasting challenges of starting from disclosure to large-scale notification and attempting newer communication channels and strategies to mitigate the vulnerabilities in time.

5.2 The Comparison of Different Scenarios

To understand how the finders in the selected work adopted and contributed to best practices, we describe and compare their experiences based on the assessment stages in Section 4.1. The comparison follows the order of the five stages: Pre-Assessment, Communication Channel, Messaging Infrastructure, Disclosure Policy and Message, and Post-Review.

5.2.1 Pre-Assessment. Once a new vulnerability is found, the finder should assess the possible impact, affected parties, and the possible risk associated with that impact. This will determine the best approach to inform stakeholders.

All disclosure operations [4, 6, 19, 33, 34] initiated the coordinated vulnerability disclosure directly to affected vendors with newly found vulnerabilities and later delegated their disclosure to support organisations. Before their disclosure, most finders could identify several vendors with bug bounty [6] or tracking program [19], and a short list of direct disclosure contact information [4, 6, 19, 32–34], which ranges from 5 to 14 affected parties due to limited capacity or testing environments. However, most finders faced challenges such as limited contact information of other stakeholders and the potential development to large-scale disclosure. They then consulted national CSIRTs, CERT/CC (VINCE), or NCSC-NL, except for the researchers in [19]. The impact scale later increased dramatically from the cooperation with support organisations, which is presented in the Post-Review in Table 1. Despite the lack of contact information in the pre-assessment, the disclosure parties could still mitigate the challenges with the support organisations.

The notification operations are vulnerability notifications to the stakeholders, with hosts or domains remaining vulnerable after public disclosure. The finders either leveraged existing datasets [9] or performed network scanning [30] to assess the impact scale of the existing vulnerabilities. The large scale of the notification operations listed in Table 2, unlike disclosure operations in Table 1, has reached significantly higher host numbers ranging from ten to a hundred thousand. In the latest work [4], the affected IPv4 hosts have reached a million at an internet-wide scale. On the other hand, the two notification operations [23, 39] have fewer affected parties due to the partnership with a medium-sized ISP with its selected customers. In addition, most notifications included more than one vulnerability or security issue of the vulnerable hosts and domains. Hence, the efforts to estimate the exact number of affected parties increased as well.

As a result, the main challenge of vulnerability notification is how to inform diverse stakeholders and handle multi-party scenarios at scale. Based on the initial estimation of the vulnerability characteristic, impact scale, and affected parties, the next step is to choose the most efficient communication channels and messaging infrastructure to inform stakeholders effectively.

Channel & Infrastructure	Work
Email	Individual Account [4, 19, 24–26, 32, 34]
	Dedicated Account [9, 15, 16, 23, 39, 40]
	Not Specified [6, 10]
Coordinator Delegation	[4, 6, 15, 26, 32, 34]
Website	[4, 6, 9, 15, 34, 40]
Survey	[10, 15, 25, 40]
Phone	[16, 23, 26]
ISP Intervention	[23, 39]
Community & Meeting	[19, 32]
Post	[16, 26]
Social Media	[26]
Shadowserver Foundation	[4]

Table 3. Channel and Messaging Infrastructure

5.2.2 Communication Channel. Selecting a communication channel remains critical [38] to vulnerability disclosure and notification. Depending on the pre-assessment, a finder can select single to multiple communication channels to reach out to stakeholders at scale, as shown in Table 3. With the current guidelines, there is still no simple decision on channel selection considering the tradeoffs between contact information retrieval and resource capacity, as discussed in all selected works.

For vulnerability disclosure, CVD as best practice is provided in guidelines and gradually adopted by vendors [37]. However, improvements for different scenarios are still being made to best practices. Boucher et al. [6] identified their initial list of affected vendors with bug bounty programs, direct disclosure contacts and outsourced vulnerability platforms. Although they succeeded in most bounty programs, they faced delayed responses or complications in follow-up conversations with outsourced platforms due to their prioritisation of vulnerability reports [37]. They concluded that direct disclosure contacts or bounty programs of vendors might be more effective in extended discussions for their disclosure.

In comparison, Moura et al. [19] experienced late answers and mitigation schedules with a well-known vendor’s direct contact and a bug tracking system. On the other hand, the finders in most work [4, 6, 32–34] delegated the

notifications to coordinators such as CERT/CC with VINCE and national CSIRTs. Finally, researchers in [19, 32] attended conferences and meetings to reach out to vendors or operators in related communities.

For vulnerability notification, finding an optimised channel to inform the stakeholders at scale turns out to be more challenging than vulnerability disclosure. The most significant difference is that the coordinator delegation to national CSIRTs has been reported as ineffective due to the large scale that went beyond the coverage of the support organisations [15, 26]. The finders in work [25, 26, 40] exhausted multiple communication channels shown in Table 3 and empirically studied the effectiveness of each channel with the remediation rates by time and feedback from affected parties. From their conclusion, email still remains the prominent channel for conducting large-scale notifications with the best coverage rate despite the obvious pitfalls, such as a high bounce rate, spam filter, and low awareness of recipients.

Similarly, the same concerns were reported in [10, 15], which used email as their primary channel. In more recent years, notification operations in [9, 24] adopted best practices derived from the previous work and narrowed their selection to email with a website as support. On the contrary, Maaß et al. [16] alternatively selected post and email to compare the effectiveness of both and provided phone support to affected parties. With the considerable amount of manual contact retrieval efforts for email and post, they figured the post could be an effective but costly channel in their nation. Eventually, the researchers in [9, 16, 24] all confirmed that the aforementioned issues of notifying stakeholders with email remain.

Across all the selected work, email is the widely used communication channel in initial messages and discussions with vendors and end-users. The main challenges of email are still contact retrieval and low delivery rate. The finders scripted database queries using WHOIS either with purchased database [25, 26] or with online query service [9], to retrieve email contact information. Although the researchers in [9, 25] mentioned RDAP as a potential alternative, none attempted it. However, it was reported in [11] that RDAP has not caught up with the coverage of the existing WHOIS database despite the protocol being introduced to improve contact sharing. Maaß et al. [16] confirmed that manual contact retrieval, at best, does not guarantee accurate contact information either. Aside from the contact retrieval issue, email is constantly challenged by high bounce rate [10, 15], spam filter [9, 25], and low incentives of recipients to read messages [40]. This eventually results in a low delivery rate to the stakeholders.

Nevertheless, a dedicated scalable notification system may be a solution as researchers and an ISP achieved better results with their walled-garden notifications than email [23, 39]. Furthermore, the recent ongoing work [4] partnered with Shadowserver Foundation, which actively measures the impact and notifies its subscribers at scale. It is a new attempt at a communication channel, and the outcome seems promising.

5.2.3 Messaging Infrastructure. A finder will build their messaging infrastructure or delegate it to support organisations based on the selected communication channel. The common practice of outgoing email and website is using a registered individual or disclosure-specific account with the domain name of the finder’s organisation to increase the delivery rate and trust of recipients [9, 15, 25, 26]. The email account selection of each work is presented in Table 3.

The dedicated account practice is to mitigate the email notification challenge of spam and phishing mitigation nowadays. Due to the increasing spam and phishing, more and more measures are in place to prevent the delivery of these messages. In the early 2000s, it was possible to spin up a mail server and immediately send out an email notification to thousands of recipients. These days, there are many different standards associated with sending out emails (SPF, DKIM, DMARC, etc.) [15], and the reputation of the mail server is taken into account before an email is delivered.

Although a finder or its organisation can maintain their messaging infrastructure, it is also reported in [9] that their email infrastructure is partially outsourced to a mail server, Microsoft Exchange. Their mail server introduces several restrictions, such as limited account control and email-sending rate, which prevent sending out large amounts of messages [18] efficiently. This makes it harder for researchers to perform large-scale notification operations using email. This also resonates with the trends of vendors outsourcing vulnerability platforms, which limit the reachability from the sender to the responsible parties, the client of the outsourced platforms [6].

There are disclosure and notification operations delegating the messaging to national CSIRTs (such as NCSC-NL), CERT/CC with VINCE [7], and Shadowserver Foundation. These are listed as Coordinator Delegation and Shadowserver Foundation in Table 3. While VINCE serves as a disclosure database with notification toward vendors [6, 33, 34], national CSIRTs have their mailing list or website to inform vendors and end-users [4, 15, 26, 32]. In particular, Shadowserver has become a newer notification delegation option to its subscribers, including vendors and end-users [27], such as ISPs [39], domain owners, and network operators [4]. Besides, if a finder works with an organisation with dedicated communication channels, such as an ISP notifying its customers, there can be a more efficient way to trigger action from the recipients [23, 39]. A similar notification can also be seen in [9, 15, 40], where domain name owners and cloud providers use their notification systems to prompt their customers, website or service owners, to take action.

5.2.4 Disclosure Message. The formulation of the disclosure message can determine the attention of the recipients and whether or not to respond and take action [38]. The tradeoffs of length and details of content, such as remediation and security suggestions, are extensively discussed in [9, 15, 24–26, 39, 40], where they share not only their disclosure message templates but also the feedback from stakeholders.

The approach in [25, 26, 40] is to provide brief vulnerability information, affected systems or hosts, and their disclosure purposes in the initial messages. The message prompted the recipients either to respond to their emails or to check a webpage for extended information on vulnerabilities and remediations with the automatically generated token of each message by the finders. This way, the sender could study the response rate and read the message with a dedicated web backend. Moreover, the finders can lower the chance of information leak in case of the wrong recipients or parties. Furthermore, disclosure messages could be embedded with HTML content, such as the logo of the disclosure party, to further check if a recipient loads the full message. However, due to the spam filter and recent email client loading mechanism, extensive embedded HTML content is no longer a suggested method confirmed in [25, 40]. From earlier work [15, 25, 40] to recent publications [9, 24], it has been confirmed that plain text is the suggested way with less distraction and distinction from phishing messages.

Lastly, in large-scale vulnerability notifications, providing information such as domain names, IP addresses, ports, and issues found in the vulnerable systems is recommended to help stakeholders investigate issues in time, as documented from the stakeholders’ feedback in [9, 15, 25, 40]. However, receiving parties may have certain mail filters for incoming messages, which strictly limit the message length and attachments [9]. This could hinder the case of cloud providers or domain owners with a large number of vulnerable systems running for their clients. Such stakeholders may decline the messages containing longer vulnerable host lists or attachments. This eventually makes the decision on the content more challenging for finders [9, 24, 40].

5.2.5 Disclosure Policy Implementation. Organisations present support for CVD by publishing a disclosure policy on their websites, using security.txt[13], or providing bounty or tracking programs [6, 19, 33]. Boucher et al. [6] observed vendors outsourcing their programs to third-party platforms that reveal their own policies and prioritisation on vulnerability selections. They noted that the policies and preferences of the outsourced platforms may limit the

incentive and direct message delivery to the responsible parties. In the vulnerability notification, it has been observed in [9] that most informed stakeholders still do not provide security.txt or equivalent information in their responses, but privacy policies that do not necessarily help the disclosure process. The implementation of the disclosure policies among stakeholders still requires attention.

Google Project Zero started with an outgoing vulnerability disclosure policy describing the timelines they would use in disclosing vulnerabilities. On the one hand, this has pressured vendors to work on mitigation and publish it within 90 days of the timeline. After several years, the 90-day deadline has become an accepted practice. Academic researchers have also started using outgoing vulnerability disclosure policies [22], which help build trust between stakeholders and coordinate disclosure operations. The outgoing policy has been implemented in [9, 32], where the finders presented their procedures on vulnerability handling, notification frequency, setting public disclosure schedule, and more [21, 29] in their outgoing messages. This gives the receiving party a brief yet informative message for potential procedures and conversation. Other related work [19, 24, 25, 39, 40] did not document a dedicated disclosure policy, yet did provide equivalent information and contact information in their messages for coordinating the disclosure or exempting from the notifications.

For the finders that chose coordinator delegation, ISP intervention, and Shadowserver Foundation, they also followed and presented the disclosure policy from the support organizations [6, 19, 23, 25, 26, 32–34, 39]. These delegated parties often use existing relations with stakeholders and customers to create a trustworthy communication channel.

5.2.6 Post-Review. The remediation rate of the vulnerable systems is a gripe in most work, as shown in Table 2. Although there are 57% of the vulnerable hosts patched with email notification [10], which is relatively higher than others with remediation rates from lower than 2.25% to up to around 30% [9, 15, 24–26, 40], it's worth noting that the notification was 3 weeks after the notable public disclosure. Besides, the finder had to drop 56% of the detected vulnerable hosts due to responsible administrators likely having no access to treat the embedded devices [10]. Yet, with a dedicated communication channel and trustworthy notification organisation (ISP Intervention) as in [23, 39], the remediation rate can be significantly higher; nonetheless, such a scenario requires selective recipients or extra capacity and won't necessarily fit other end-user notifications [39]. Moreover, not every disclosure operation can measure the remediation rate due to the nature of the vulnerabilities and affected parties [6, 19, 32–34]. However, the operation in [4] includes both disclosure and notification operations with a measurable impact scale. It does not provide a remediation rate since it's still a work in progress. Their result is worth observing in the near future.

As [19] states, "Vulnerability Disclosure Considered Stressful"(title). The lack of best practices in large-scale vulnerability disclosure, and especially notification, has led to finders struggling to prepare and handle the aforementioned disclosure challenges at each stage. This practice gap has motivated the finders in the selected work to adopt existing guidelines, reflect on real operations, and contribute to best practices. However, the stress and frustration of the finders deserve attention. Whether it is disclosure or notification, various vulnerability platforms [6], tracking systems [19], ticketing systems [9, 15, 40] have increased the workload of disclosure parties to deliver the messages to the responsible parties in the complex multi-party scenarios. The inaccuracy of existing abuse and generic contact information has caused false positives in contact retrieval and information leaks to the wrong recipients, which is mentioned in nearly all selected work using email as a communication channel. Aside from message delivery, despite support from national CSIRTs, researchers in [32–34] still encounter the situation that certain stakeholders did not comply with the CVD as best practice in the first place. The feedback from stakeholders is also not always friendly, either in public or private

discussions [19, 32, 33]. In certain cases, to perform timely disclosure to stakeholders, researchers still need to put in extra efforts in contacting the vendors directly despite having support organizations [32].

Furthermore, reviewing and responding to stakeholders can take time and effort for the finders. With the ticketing systems as the common practices from stakeholders, the automatic responses in large-scale notifications can result in a high amount of message content to be examined [9, 15, 25, 26, 40]. Even though automatic messages may share patterns to be categorized, the mixture of multiple languages [6, 9, 15, 40], unclear stakeholder disclosure policies [9, 24], communication systems requiring manually efforts to register and input messages [9, 40] may bring higher than expected workload to finders. This can hinder the effectiveness of disclosure and notification, and more importantly, the incentives of finders [6, 9, 19, 40].

6 Best Practices for Disclosure and Notification

In this section, we aim to examine the gap in best practices and propose a new best practice for large-scale vulnerability disclosure and notification based on what we have learned from selected work, communities, and support organisations. We follow the same structure as in the previous section to look into limitations and opportunities in the stages of disclosure and notification operations. In each stage, we discuss the common pitfalls to avoid, tradeoffs on method selection, and eventually, the suggestions to both a finder and other stakeholders on how to adopt the best practice at scale.

6.1 Pre-Assessment

Understanding the impact scale, vulnerability characteristics, vulnerability disclosure or notification, and potential stakeholders is essential to setting up a disclosure operation. Whether it's vulnerability disclosure or vulnerability notification to vendors or to end-users will lead to different communication channels, messaging infrastructure, disclosure policies, and message content. From what we observed and as revealed in the reflections of selected work, due to the lack of large-scale vulnerability disclosure and notification best practice, a finder may not fully understand efforts and tradeoffs to conduct the disclosure during the pre-assessment stage [6, 19]. For instance, researchers, ethical hackers, and practitioners may not be aware of the difference between disclosure to vendors or notification to end-users, prioritisation of the contact list, and the coverage of national CSIRT support. They then may face stress or even frustration once they start the disclosure operations, then struggle with unexpected challenges [19]. Therefore, timely consultation with CSIRTs or equivalent institutes can help a finder comprehend the potential impact of vulnerability and the scale of the notification to stakeholders, as revealed in the timeline in [32] and suggested by several support organisations [2, 8, 12, 21]. Moreover, this can also help a finder evaluate potential stakeholder responses. Finders and receiving parties may have different risk assessment standards, resulting in different definitions of vulnerability severity from both ends [1, 3]. As revealed in reviewed work [10, 15], other stakeholders may set a lower priority or don't have enough capacity to mitigate the issues earlier than the finders expect. Finally, the next common question is which combination of channel, messaging infrastructure, disclosure policy and interaction can be the most effective in each case. These aspects will be discussed in the following stages.

6.2 Communication Channel

Choosing the most effective channels to perform disclosure is the key to reaching out to stakeholders [38]. In the case of **vulnerability disclosure to vendors**, there is usually a vulnerability disclosure policy in place [6, 19], possibly indicated using a security.txt [13]. The vendor may also have outsourced this to third-party platforms such as HackerOne

and Bugcrowd [36], and having a legal agreement in disclosure [17]. If pre-assessment on the potential stakeholders or impact of a vulnerability is unclear, one can reach out to national CSIRTs to consult with a possible communication channel [33, 34]. National CSIRTs may provide notification services, coordination support or platforms such as VINCE by CERT/CC [7] to efficiently identify and inform vendors [12, 21].

For **vulnerability notification to end-users**, finding the right communication channel is a big challenge. One can first consider selecting known stakeholders with clear contact information [4, 19], then seek the rest of the stakeholders' contact information. However, one should also be mindful of the messaging prioritisation and scheduling if the response time from the initial list of stakeholders takes longer than expected [19]. Moreover, one should be aware that third-party delegation to national CSIRTs may not be the most effective method, as the interest, notification coverage, and capacity limitation of national CSIRTs may not align with the stakeholders [10, 25, 40].

We do not recommend using email to perform large-scale vulnerability notifications to end-users, even though this has been the most commonly used option. Setting up an email infrastructure for doing large-scale notifications is difficult, keeping in mind all of the spam prevention tools currently in use. This comes on top of the difficulty of actually finding contact information for systems on the Internet. The accuracy of the contact information presented on web pages is not guaranteed [16]. Finding contact information for IP addresses is notoriously hard. Although WHOIS and RDAP are methods to retrieve the contact information, the current results of both are often not accurate [11]. Moreover, the contact information available is often meant for abuse notifications, not for vulnerability notifications. While the 'security.txt' standard [13] works for websites, there is no such alternative for IP addresses.

Depending on the affected parties, one can consider reaching out to key communities or platforms to support remediation [6, 19]. For large-scale notifications, the use of Shadowserver as a notification channel seems most promising [4]. Shadowserver can perform active scans and has trusting relationships with key stakeholders that support the notification infrastructure. This has the added advantage that end-users are not overwhelmed with notification campaigns from different researchers. Phone calls and posts are more of an option when stakeholders suggest doing so [16, 25].

6.3 Messaging Infrastructure

The messaging infrastructure will depend on the selected communication channels. Researchers should follow the indicated preference of vendors in using the contact method, usually email, or messaging platforms such as bug bounty or VINCE.

If an email infrastructure is still used, then we recommend that the sending email address be from a known domain name or with an organisation to increase the delivery rate [9, 25, 31]. One should also be aware of the implementation of their mail service; with the mail service outsourcing trend, there can be rate limits and extra policies to examine beforehand [9]. Be aware that recipients may send automatic responses, divert to ticketing systems, request feedback forms [9, 10, 25, 40], or outsourced platforms with different disclosure policies [6, 32]. It should be noted that the effectiveness of large-scale email notifications leaves a lot to be desired, as can be seen in Table 2.

Aside from the mail service, one can also provide web pages to describe the intention of the disclosure, vulnerability information, remediation, and disclosure policy. This can help reduce the content in email messages and provide a static source for stakeholders to help track the issues in the long term [9, 25, 33, 40].

The scalability of the messaging infrastructure is the biggest challenge when performing large-scale vulnerability notifications. Although organisations such as CERT/CC with VINCE and national CSIRTs with vulnerability notification

systems can help with large-scale disclosure, there is still no optimised channel and infrastructure for vulnerability notifications. Shadowserver seems to be a promising infrastructure for effectively reaching affected parties.

6.4 Disclosure Policy and Message

Composing a disclosure message is never trivial. Among stakeholders, a finder and affected parties can have different preferences and procedures for handling the messages [31, 37]. In vulnerability disclosure, vendors with bounty programs or disclosure policies may provide clear instructions or at least contact information to initiate the disclosure [36]. In contrast, recipients of the vulnerability notification may not provide enough information on how they will handle a disclosure message. Network operators may prefer extensive information that includes more details and remediation [21, 31], given that the affected party follows a certain time constraint policy on remediation [9]. Meanwhile, cloud providers or domain owners may forward the message to their clients with limited communications [9, 15]. Eventually, one should be aware that not every stakeholder would accept longer messages or attachments regarding the mail server filter, ticketing systems, and spam filter [9, 25, 40]. As a result, we recommend that a finder ensure that the initial message remains brief and does not necessarily reveal every detail of the vulnerability in case of an information leak or legal action [29, 31].

In conversations with stakeholders, one should consider that large-scale vulnerability disclosure and notification may get manual or automatic responses from various communication systems in different languages. In most cases, we have seen English used in the responses; other languages are used as support [9, 10, 15]. Messages in different languages may increase the processing time and cause confusion, especially if disclosure policies are presented in non-native languages to a finder or a receiving party. Besides, when using stakeholders' communication systems, a finder may need to put extra effort into reformulating the messages based on the limitations of the disclosure form or editors in the provided text system [9].

All things considered, we recommend that a finder and support organisations establish an outgoing disclosure policy [21, 22, 29], which includes legal terms, disclosure schedules, message templates, or exemptions, as implemented in [9, 24, 32]. This can let recipients understand the disclosure procedure from a finder and protect the finder from unwanted behaviours such as legal actions [17] and public criticism [32]. Moreover, we recommend that the stakeholders include a disclosure policy [8, 21, 29] or security.txt [13] in their disclosure programs or responses. This helps a finder to initiate the disclosure and notification operations with the stakeholders with better preparation. As we observed in the community and selected work, disclosure policies and equivalent documentation are not widely implemented, and this has resulted in both finders and receiving parties having inefficient communication.

Last but not least, one should be aware of the stance of stakeholders on disclosure or notification best practices. Not every stakeholder may want to adopt the best practices for different reasons. This has been documented in two vulnerability disclosure operations [32, 33] with vendors refusing to participate in the remediation schedule despite having a national CSIRT as coordinator. Still, we encourage stakeholders to adopt best practices and participate in disclosure or notification operations.

6.5 Post-Review

Measuring the impact after vulnerability disclosure and notification can help reflect on this process and improve best practices. If a vulnerability or a security issue is traceable by performing network scanning, measuring with stakeholders, or communicating with end-users, it can be valuable to record the remaining number of vulnerable systems after disclosure or notification. Additionally, providing a timeline as figure [6, 10, 19, 25, 26, 32] or as text [9, 24]

for each disclosure stage can help understand the operation development and its impact over time. These aspects have been covered well in our selected work, revealing the tradeoffs and considerations in different scenarios. Aside from monitoring vulnerable systems and messaging infrastructure, what the finders encountered and stressed during their operation is also worth recording. As revealed in nearly all reviewed publications, handling disclosure or notification procedures can be a nerve-racking trial. It is crucial to have evolving best practices to help a finder prepare for the challenges and ease the stress during disclosure operations. With the fast-changing nature of the network landscape and the growing number of vulnerabilities, it is important to have best practices up to date and mitigate security issues in time.

We have seen publications focusing on the exploits, attacks, and network traffic before and after the public disclosure. However, the work focusing on large-scale vulnerability disclosure and notification is relatively less seen in the community, which is also mentioned in [9, 19, 25]. Further, we have observed that not every finder has the capacity and prior experience to conduct disclosure or notification operations and finish the documentation within the academic publication period. Nevertheless, we have seen researchers in [4, 9, 24] could learn from the prior best practices and contribute to large-scale notification practices. Therefore, we encourage researchers, ethical hackers, practitioners, and operators to document their disclosure or notification operations with their own experiences, considerations, and outcomes. In the selected work, the tracking period can range from weeks [10], months [9, 39], or more than a year [24] if the situation permits. It could be a webpage [5, 34] and followup publications [6, 10, 24, 25, 35] to present disclosure or notification updates.

7 Conclusion

The practice of doing academic research on vulnerabilities is growing in popularity. Even though we have best practices for vulnerability disclosure, this does require more attention when this scales up. We note that there is a difference in practice between vulnerability disclosure and vulnerability notification, especially with regard to the stakeholders involved. We have analysed trends in academic work and the security community, and propose new best practices to bridge the gap between the existing guidelines and the limitations in actual operations. We believe that our best practices give researchers, ethical hackers, and practitioners a clear direction to inform stakeholders at scale with less friction. With our suggestions, stakeholders can prepare for the disclosure or notification message response and mitigation. We encourage all the stakeholders, including finders, vendors, and end-users, to not only bring in the best practices but also document and publish their experiences to help improve future disclosure and notification operations.

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