Rescuing the End-user systems from Vulnerable Applications using Virtualization Techniques

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Abstract
In systems owned by normal end-users, many times security attacks are mounted by sneaking in malicious applications or exploiting existing software vulnerabilities through security non-conforming actions of users. Virtualization approaches can address this problem by providing a quarantine environment for applications, malicious devices, and device drivers, which are mostly used as entry points for security attacks. However, the existing methods to provide quarantine environments using virtualization are not transparent to the user, both in terms of application interface transparency and file system transparency. Further, software configuration level solutions like remote desktops and remote application access mechanisms combined with shared file systems do not meet the user transparency and security requirements.

We propose qOS, a VM-based solution combined with certain OS extensions to meet the security requirements of end-point systems owned by normal users, in a transparent and efficient manner. We demonstrate the efficacy of qOS by empirically evaluating the prototype implementation in the Linux+KVM system in terms of efficiency, security, and user transparency.

1 Introduction
The proliferation of computing end-points like laptops, smartphones, and other hand-held devices with internet connectivity at the fingertips of gullible users pose security challenges of different kinds. One such challenge is securing devices owned by end-users with little or no understanding of the security intricacies of a complex and layered computing system. We refer to these device owners as unwary users in this document. In systems owned by unwary users, security attacks are often mounted by maliciously sneaking in, using security non-conforming actions of the unwatchful users. For example, users may download malicious files from email or web applications and, despite system generated warnings, allow the virus to take over the system by granting administrative privileges [60]. In this context, OS support for different user privileges [4] fails to protect the system as normal users being the owner of their systems also have the system administrator privileges. Restricting the device owner privileges is not very user friendly and may raise usability concerns in general. In this paper, we propose OS enhancements using virtualization technology to improve the security of normal user systems in a transparent and user-friendly manner.

Virtualization techniques [5, 26, 42, 65] provide support for strong isolation across applications, used to intensify system security at different levels [59]. Efficient sandbox techniques [25, 31, 61] to protect applications and the OS from one another, isolation of potentially malicious devices and drivers [30, 48, 56], detection and mitigation using virtual machine introspection (VMI) [7, 47, 51, 66] are some example applications of the virtualization technique in the security context. Further, hardware enhancements like Intel SGX [14] and Intel CAT [23] can be used with virtualization solutions to strengthen security [3, 18, 22]. In the context of normal user end-point devices, hosted virtualization solutions like KVM [26] and HyperV [42] can be leveraged to address security concerns by executing applications or system components that are potential entry point of malware in isolated VMs. For example, in Microsoft Windows10, the end-user is provided with a VM to run vulnerable applications in a sandbox using underlying Hyper-V hypervisor [41]. While an ideal solution would entail the same security guarantees as that of VM-based solutions along with the efficiency and user experience of a native system, achieving these three goals in their entirety and at the same time is non-trivial because of the following reasons.

First, for any VM-based solution, it is difficult to remain behind the scenes and still provide a cohesive view of the whole system. Virtualization based approaches to provide secure computing platforms to unwary users present two separate views of the file system and display interfaces (e.g., [41]). For example, if a browser application is executed within a VM (for enhanced security) and a file is downloaded, accessing the file through the file system interface provided by the VM requires accessing the file system within the VM. Similarly, to access the user interface of the applications (specifically GUI applications), the user is required to access the VM console which may not be very convenient. Second, any security solution for unwary users should be simple to use and not involve additional actions from the user. With existing VM-based solutions, the end-user is burdened and trusted to categorize applications and decide if a given application is required to be executed within the VM as this requires non-trivial expertise. For instance, a PDF viewer application may be treated as secure for all valid PDF files but becomes a potential security threat when opening a file downloaded...
through a browser or email client. Further, if intelligent software agents on the machine take over the responsibility of deciding the access to applications and files, the user should still be able to execute the applications (with some warning messages), instead of being completely restricted from using the application. Third, the quarantine system should be efficient in terms of CPU and memory usage. While VM-based solutions are expected to result in certain overheads, the overheads should be as minimal as possible.

Considering the challenges involving multiple dimensions, a practical solution should strive to reach a middle ground balancing the security, transparency, and performance aspects of the end-user systems. Towards this objective, we present the shortcomings of native systems and container-based solutions and, present two straw man (but unexplored in this context) VM-based solutions created combining techniques like shared file systems and remote display access mechanisms (§2). Further, we motivate the need for a quarantine framework with fine-grained control over resource exposure and enhanced security monitoring capabilities.

We propose qOS, a set of OS extensions along with a VM sandbox to enable a holistic quarantine environment which provides the user experience of a native system in a resource-efficient manner. In qOS, a hidden VM (referred to as the qVM) is configured as the quarantine environment to take over the execution from the base machine when required (§3). Further, for end-user transparent file and display operations, the host OS provides a controlled and monitored channel for applications executing in the qVM. For example, when an email client is executed from the base machine, the real execution happens within the VM (without the user knowing it) and the user interacts with the application just like she would on a normal system. Moreover, when the user downloads a file (e.g., text file) through an email client and tries to open it using a text editor, the text editor also executes within the quarantine. Compared to simple VM sandboxes, qOS weakens the security in the quest for native-like user experience, but it offers better security compared to other non-transparent VM-based approaches and enables monitoring and filtering knobs in the framework (§5).

We evaluated our system in the Linux OS for different end-user applications like mail client (thunderbird), browser (dillo), PDF viewer (evince), text editor (gedit), text-based browser (elinks), HTTP client (wget), secure text-based clients like ssh, scp and sftp (§6). The experimental analysis shows that qOS performs better than NFS-based straw man solutions in terms of CPU and memory efficiency. Further, while achieving the objective of being behind the scenes, qOS improves display performance over remote desktop-based solutions by more than 15x. In short, qOS strikes a balance between the three design aspects as compared to the straw man solutions; it offers better security guarantees and complete invisibility with lower resource overheads.

In this paper, we make the following contributions:

- Provide operating system enhancements to build a holistic quarantine environment using a hosted hypervisor to meet the security requirement of systems used by normal users who have very little expertise in computer system security.
- Design and implement a working prototype solution on Ubuntu Linux distribution with KVM hypervisor, which supports different GUI and command-line applications.
- Empirically demonstrate the efficiency of qOS compared to partial alternate solutions.

2 Motivation

According to a security study in 2018 [60], a significant number of attacks are performed exploiting the unmindful actions of end-users, especially through internet activity. To build secure systems for end-users, a threat model should be defined before exploring different solutions.

 Threat model: For unwary user-owned systems, we assume at the time of installation, there are no malicious files in the system and, the vulnerability of installed applications and the OS can be exploited by different types of malware by entering the system through internet activity. We also assume that the user is not a security expert and can be tricked to gain administrator privileges from these malware. With a typical VM sandbox, we assume that the hypervisor is the trusted computing base (TCB) and can not be compromised through standard guestOS and hypervisor interactions.

2.1 Why VM based quarantine?

Native execution may allow malware to exploit vulnerabilities in the code through attacks like buffer-overflow [46], integer-overflow [16], return-oriented programming [8, 10, 29] due to the large attack surface. Even though modern operating systems employ defense mechanisms like Address Space Layout Randomization (ASLR) [57], stack guard [15] and Data Execution Prevention (DEP) [40], an unsuspecting user could inadvertently turn off these protections and allow malicious code to run on her system. For example, while installing any software on a device owned by an unwary user (with admin. privileges), the user may unknowingly agree to disable the ASLR feature compromising the security. Moreover, malicious devices and device drivers can be potential entry points for attackers. IOMMU based defense mechanisms to stop malicious devices can not provide defense against buggy device driver code when the device driver runs with the OS privileges.

Containerization is a popular, lightweight solution employed for isolation and confinement [58]. While containers provide namespaces for many subsystems including the file system, container-based solutions still depend on process level memory isolation techniques. This basic limitation of containers allows applications to break out of the container...
and gain root access on the host [2, 45]. Virtualization provides a stronger form of memory isolation by enabling and managing separate address spaces between the VMs and the hypervisor using techniques like virtualized memory management unit (MMU) [43, 67]. Another advantage of virtualization over containerization is the flexibility at the hypervisor layer to enforce security policies, and employ detection and mitigation of security attacks [52, 54, 56, 68].

### 2.2 Possible VM-based solutions
A simple VM as a quarantine environment like Windows sandbox or a VM on a hosted hypervisor like KVM, apart from being overt, depends on the end-users for security enforcement. Moreover, the end-user has two file system views and separate display interface for the sandbox VM. One possible approach to present a single file system view to the end-user is to use a network file system (NFS) from within the VM. For display, two existing techniques—(i) Virtual Network Computing (VNC) based VM console access, (ii) X11 forwarding based application GUI access from the host—can be used. Figure 1 shows the two straw man approaches combining the NFS with the display access techniques. For file system transparency, user home is mounted in the VM to allow the user to share the same file system view (at least for the user’s home directory). We refer the NFS mounted scheme combined with VNC display access as vncNFS and NFS mounted scheme combined with X forwarding based display access as xNFS. vncNFS can be thought as an extension to Windows Sandbox feature [41] where transferring the executable and its associated files to the sandbox is not required because of the NFS-based shared FS view. Another possible alternate is to use light-weight VMs [1, 27, 36] to host applications but, even in this case, similar support for unified FS and display view is required.

### 2.3 Why qOS?
The VM-based solutions presented above are not ideal as they do not satisfy all the requirements (See Table 1). We lay down the aspects of an ideal solution and discuss the compromises made by vncNFS and xNFS which leads to the design objectives of qOS to achieve a better tradeoff.

#### Transprenency: Ideally, the end-users should not be able to feel any difference in the way they interact with the system. Specifically, the desirable solution should provide a single file system view and present an application interface which is same as the interface in native execution. The problem of user transparency remains as the user has to access two different machine interfaces (with vncNFS) and the application is launched from within the VM using the VM-level configurations and libraries (for both vncNFS and xNFS). In qOS, we achieve better transparency where applications are (re)launched in quarantine mode (if required) to provide the user experience like a native system.

#### Security: The ideal solution should be as secure as a case of executing the vulnerable components within a VM where the hypervisor is the TCB. Additionally, the security should not assume end-user expertise and should be non-restrictive i.e., the end-users may execute any arbitrary application without compromising the host system security. NFS sharing across the VM and the host has to be carefully designed such that the exposure is limited. Even with a carefully designed NFS, exposed host file system sub-tree when accessed by other applications executing on the host can break the security. For example, consider a case when a malicious PDF file is downloaded using the browser executing within the VM and saved onto the NFS share. When the same file is opened from the PDF viewer executing natively on the host, the security is compromised. Moreover, as the applications are treated as secure or vulnerable statically (irrespective of the inputs) and executed within the VM or on the host, it will have consequences with respect to security and efficiency. qOS addresses these problems by separately classifying applications and inputs to the applications, not allowing any user-privilege change from applications executing from within the VM and, enforcing fine-grained access control.

#### Performance: The ideal performance is tricky as it can not be the same as the native system; an approximation can be to achieve the same performance of executing the application in the VM with a local file system and without any overheads due to display activities. While the virtualization overheads, in general, are well known, the performance overheads of

| Design goals | Sandbox using VMs | vncNFS | xNFS |
|--------------|------------------|-------|------|
| Transparency (being hidden) | None | Partial (only FS) | Better than vncNFS |
| Security | Hypervisor as TCB | Increased attack, surface, no in-built monitoring and control support | Similar to vncNFS |
| Performance | Well studied | Unknown | Unknown |

Table 1. Comparison of solutions using VM as a sandbox.
a system like virtNFS and xNFS in terms of additional resource usage should be compared against qOS.

3 Design of qOS

Figure 2 shows the high-level architecture of the proposed qOS system. The core design principle of qOS is to execute the untrusted and exposed applications in a VM known as the quarantine VM (qVM). To keep the host system secure, qOS employs a safe access principle as explained below. Applications and files are categorized into three categories—(i) safe (shown in green), (ii) unsafe (shown in orange) and, (iii) unverified (shown in yellow). Safe applications and files are allowed to be executed and accessed in the native mode on the host. Unsafe applications are executed within the qVM and unsafe files are deleted once they are detected. Unverified files are created by unsafe applications during their execution and are not allowed to be accessed by any process in the host. If the user must use an unverified file, the application is launched within the qVM. Unsafe applications can be created by installing downloaded applications in the qVM and are allowed to execute within the qVM. Unsafe applications are executed using the qAgent. qOS maintains and enforces the safe access rules at all times. There are two major components in the qOS solution. On the host, qSecurityMonitor (qSM) is responsible for enforcing the security policy and execution policy. In the VM, there is an agent (qAgent in Figure 2) which communicates with the qSM to carry out application hosting and split-execution.

Life cycle of qOS: We assume that, when qOS is installed on the system, the host system is in a clean state i.e., there are no unsafe files in the system and applications are correctly categorized as safe and unsafe (no unverified files/applications in the system). When the user tries to launch an unsafe application, the qSM dispatches the application into the qVM through the qAgent. The qAgent is responsible for the split execution by forwarding the file and display related operations to the host through the qSM. The qSM monitors each request from the qAgent and updates the file and application state (to unverified) if they are created/updated from the qAgent. A periodic security analysis (by a security expert program and/or human) is performed on all the unverified entities to classify them as safe or unsafe. At this point, if there are unsafe files, the security expert can analyze the genesis of the file by examining the qOS logs to decide further actions which may include reimaging the VM. Moreover, if some applications are classified as safe, they may be installed on the host to allow native execution afterwards. Note that, the offline security analysis is a non-mandatory requirement (for efficiency) as qOS design is flexible to execute applications and access files either from the host or the qVM.

3.1 qSecurityMonitor

The qSecurityMonitor has the following subsystems:

Certifier: The certifier is tasked with classifying entities as safe or unsafe for execution on the host system by employing two mechanisms. First, this unit is equipped with a configuration drafted by a security expert, based on which it takes the classification decisions. Second, it performs runtime monitoring of operations performed by applications executing within the VM to update the status of applications and files. The certifier subsystem extends the file meta-data to store additional information regarding the file classification state to address the above challenges.

Execution Monitor: Execution of the unsafe entities is performed by splitting the processing across the qVM and the host. The execution monitoring unit handles this bifurcation by co-ordinating with the qAgent. Unsafe applications can be launched in two different modes—(i) local mode (qOSL) and (ii) remote mode (qOSR). In local mode, the application binary and all libraries are loaded from the qVM itself, while in the remote mode, the binary and libraries are loaded from the host system. The remote mode provides the flexibility of application launch and file access independent of their location. The execution monitoring is also responsible for handling process termination and host state cleanup.

HostOS Gateway: Split execution of applications within the VM requires accessing the display and file system of the host to realize user transparency. All the file and display operations are intercepted by the qAgent and forwarded to the HostOS Gateway through the shared channel (Figure 2). HostOS Gateway allows limited file/GUI APIs on the host side and closely monitors the robustness of each communication by checking the parameters of each invocation. Any non-confirming message from an application results in termination of the application along with a notification to the
We have implemented a prototype of qOS in the Linux + KVM system where qVM is a Linux VM. Both qAgent and qSM are implemented as kernel modules in the guest OS and host OS, respectively. Minor modification to the guest OS kernel is done to intercept the system calls.

Figure 3 shows the working of different qOS components when an unsafe application is executed from the host. The Execution Monitor intercepts all exec calls to find out (from the Certifier) if the application is unsafe and should be launched in the qVM. Next, the Execution Monitor communicates (using the communication channel) with the application manager (shown as ApplicationManager in Figure 3) to launch the application in the qVM by providing information like executable path, arguments and mode of execution (local or remote). The process context on the host OS (shown as the Split-context) executes the gateway code where it waits to receive any message from the qAgent. When the application process executes in the qVM (shown as the Split-application), the system call interceptor (shown as Syscall Interpreter in Figure 3) forwards the file and display related system calls to the host OS gateway. Similarly, if a file is mapped to the process virtual address space (using mmap) and a page fault occurs, the Filemap handler serves the request by communicating with the host OS gateway. The syscall interceptor maintains the correlation with the host file descriptors to handle subsequent operations. When any file is opened in write mode, the HostOS Gateway notifies the Certifier to update the file category information (Refer §3). Once the split-application within the VM exits, the split-context on the host is cleaned up.

4.1 File and display channel
Whenever the split-application makes an open system call, the system call interceptor decides whether to open the file in host or qVM. Devices, sockets, pipes and libraries (in local mode) are opened in qVM itself. For all other regular files, the system call interceptor sends a request to the split-context waiting in the host OS gateway. The host OS gateway opens the file in the host and returns the file handle to the system call interceptor. The system call interceptor maintains a per-process mapping of the file handles to serve the system calls like read, write etc. Operation on the standard file descriptors (stdin, stdout and stderr) are always forwarded to the host. Similarly, for GUI display operations, all the X client socket operations are forwarded to the host. In the current implementation of qOS, there is a single process instance (split-context) in the host side for each application irrespective of the number of processes/threads in the qVM. On the qVM side, the system call interceptor is executed in the context of the process/thread that invokes the system call. Therefore, when a process/thread is created/terminated in the split-application, the file reference information is updated in the split-context on the host. The primary reason for using an N:1 design is security i.e., to avoid DoS attack on the host (See §7). We avoid blocking I/O calls and use adaptive I/O event handling to perform I/O multiplexing.

File mmap: Mapping a file into the process address space using mmap system call requires special handling if the file belongs to the host system. One of the strategies could be to populate the address space by reading the whole file at the time of mapping which may result in slow mmap performance. qOS adapts an on-demand strategy by registering a fault handler for the filemap region and serves the page faults by reading the file content from the host. We have observed that for all applications most mmap calls are used to map the dynamic libraries into the address space and only a part of the library is actually used during the execution. It is possible to design more sophisticated schemes (e.g., populating pages in the vicinity of fault address) and left as a future direction.

I/O multiplexing: Event driven I/O using select and poll require to be split carefully. When the file descriptor set

Figure 3. Implementation of split execution using qVM. Communication channel (shown in orange) is used to pass messages between the qVM and the host. HostOS Gateway logic is executed in the application process context.
(FDSET) elements are all local fds (like pipe, network connections etc.) or all host fds, then the handling is trivial. However, when the FDSET is a mixture, we have to wait for the I/O event in both the host and the qVM. We have designed an adaptive strategy to invoke the guest OS and host system calls in turns with an appropriate time slice determined dynamically based on the past behavior and application profile. While we have implemented an adaptive strategy for the select system call, for poll system call we juggle between the guest OS and the host with a fixed time slice of 10ms.

4.2 Communication channel

The communication channel is implemented using the shared memory region between the qSM and the guest OS enabled through ivshmem [35]. The shared memory region is divided into two types of message slots—normal slots and big slots. Each normal slot is implemented as a circular queue for message passing. Each process/thread of a split-application is allocated two normal slots for communication in each direction. This allows lock-less operation on the slots for multiple multithreaded split-applications. The big slots are used to pass large messages (like binaries, file data etc.) and they need to be reserved before use. The slot allocation is performed by the execution monitor on the host side at the time of application launch or process/thread creation. The split-context on the host can wait on multiple slots to handle messages from any of the threads/processes in the qVM.

4.3 qSM: safe access principle

If the application running in the qVM creates/updates any file on the host system, the qSM does not allow the file to be opened or executed on the host system. qSM achieves this functionality by leveraging the extended file attribute feature of the Ext4 file system. Whenever a file is written from the split-application, qSM sets the extended attribute to reflect that it is unverified. We have modified the VFS layer to stop any process from opening the file in the host. A subtle (but rare) case arises when a file already in use by a process on the host is modified by a process executing within the qVM. To tackle this case, we verify the file object references in the in-memory inodes to ensure that the file requested to be opened for writing from the qVM is not in use by any other process on the host.

4.4 Subtle issues and optimizations

We encountered and addressed many corner cases during the implementation of qOS. Some of them are highlighted here. First, killing a split-application from the host using signals (e.g., CTRL+C) requires the kernel signal handler invocation but rare) case arises when a file already in use by a process is not in use by any other process on the host. A subtle is allocated two normal slots for communication in each direction. This allows lock-less operation on the slots for multiple multithreaded split-applications. The big slots are used to pass large messages (like binaries, file data etc.) and they need to be reserved before use. The slot allocation is performed by the execution monitor on the host side at the time of application launch or process/thread creation. The split-context on the host can wait on multiple slots to handle messages from any of the threads/processes in the qVM.

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5 Security Analysis

In this section, we present a comparative security analysis across four different quarantine environments—(i) VM as a quarantine with local file system and display, (ii) uncNFS (explained in §2), (iii) xNFS (explained in §2), and (iv) qOS. Table 2 shows the overview of security threats and their implications on different setups. Note that, the threats shown in Table 2 can impact the native systems easily compared to all the other setups.

**Virus entry to host FS:** One of the primary design objective of qOS is to address the security issues caused due to the actions of unwary users. A malicious entity (e.g., malware, trojan etc.) can enter into the system because the user can accidentally download it through a browser or email client. qOS provides the same level of security as the simple VM setup as qOS prevents any application from host accessing the malware. The uncNFS and xNFS setups can be penetrated because once the file is downloaded and accessible natively, the host system becomes vulnerable. A compromised application from the qVM can corrupt accessible files as neither qOS nor a trusted VFS layer enforcing the user ACLs correctly can stop any legitimate write access. To address this kind of attacks, intelligent monitoring techniques proposed in gVisor [69], MBOX [25] etc. can be incorporated into the qOS framework.

**Control-flow hijack:** The attacker exploits the bugs or vulnerabilities in applications by passing carefully crafted inputs to update the file usage count on the host side. Third, some applications use UNIX socket control messages [32] to setup file descriptors in other processes which need to be tracked by the qAgent. Fourth, the close_on_exec flag is set/unset using different system calls (open, socket, fcntl etc.) which should be tracked to avoid file descriptor leakage on the host. Fifth, it may happen that an application (safe) running on the host, due to some user input or otherwise, tries to open an unverified file. In such a case, the file access is prevented and the user is informed of the unsafe access. There is a provision in qOS to temporarily mark such an application unsafe and re-execute the application to launch it using qVM (if required using the remote mode).

One of the primary optimizations is to minimize the extensive communication between system call interceptor and the host OS gateway. To accomplish this, we employ techniques like write-combining and read-batching. In write-combining, qAgent uses a big slot to store many write requests on the same file and sends a single write request. In read-batching, the system call interceptor in qAgent reads bigger chunks to serve subsequent read requests from the split-application [9]. Note that, these optimizations require careful handling of consistency issues caused due to simultaneous writes. In simultaneous write scenarios, the optimization is turned off and normal operation is carried out.
to gain access to the system. In the quarantine execution model, all the attacks are localized to the VM. However, both \textit{vncNFS} and \textit{xNFS} assume the NFS server to be bug-free such that even if the NFS client in the VM is compromised, NFS server at the host remains unimpacted. Further, both \textit{xNFS} and qOS use the X-server executing on the host to serve the requests and assume that the X-server to be secure. For qOS, the VFS layer is trusted to enforce the user ACLs correctly which allows qOS to detect applications trying to access files without having necessary permissions.

\textbf{Denial of service:} With xNFS and vncNFS, any malicious application in the VM can perform a lot of file operations to impact the applications executing on the host. For example, a compromised process in the VM can create and delete files on the host in an infinite loop. This is particularly a difficult attack to stop in general. The qOS framework can identify the applications with abnormal behavior (at the HostOS Gateway) to rate-limit such operations and in the worst case terminating the application or re-imaging the qVM.

\textbf{Information leakage:} Due to complete separation of display and file systems, information leakage from the host is not possible in a simple VM setup. \textit{xNFS} and qOS (in the current implementation) can leak information through the display channel by allowing access to resources like a clipboard. qOS security monitoring can be extended to stop access to these resources as the split interface is suitable for such an extension. While qOS does not allow any user privilege change, information leakage from accessible files is hard to stop in all the setups as any file on the host with access permission for the user can be accessed.

\textbf{Other attacks:} Attacks like micro-architectural side-channel attacks are equally applicable for all the setups. Compared to native execution, this attack is difficult to perform on the virtualized system because of the noise. Moreover, hardware defense mechanisms like cache allocation techniques and, hardware enclaves can harden the system further.

\textbf{Security of qOS channels:} qOS implements the communication channel by sharing memory across the host and guest OS. Considering the worst-case scenario when the guest OS is compromised and the communication channel is used maliciously, qOS is capable of filtering out messages which can impact the host system. The messages sent through the communication channel follow a very strict format and any violation of the format can be detected at the host. Any message not meeting the message structure is discarded and the application is killed. Note that, even if the communication slots for applications are isolated, a compromised qVM OS can send legitimate messages on slots used by other applications. In such a case, the impacted applications will malfunction which acts as an indication to re-image the qVM.

While qOS provides a more security hardened solution compared to \textit{xNFS} and \textit{vncNFS}, it compromises certain aspects of security of a VM-only solution. We believe that, qOS security can be improved by employing complimentary techniques like VMI to effectively monitor the guest OS and the communication channel.

### 6 Experimental Evaluation

\textbf{Experiment setup:} To evaluate the efficiency of qOS, we performed our experiment using Linux Ubuntu-14.04LTS desktop on Intel i7 machine (eight logical CPUs with hyper-threading) with 16GB RAM. A VM (using KVM hypervisor) with two logical CPUs (pinned to physical CPUs) with 2GB RAM is used as the quarantine environment in our experiments (referred to as qVM). Our prototype implementation of the proposed quarantine environment using qOS extensions are implemented in the Linux kernel version 4.20.0 (both in the VM and the host).

For comparative analysis, we have used five different setups, as shown in the Table 3. The \textit{NoSec} system is the host system without any virtualization-backed quarantine. \textit{vncNFS} mode requires the user to access the VM desktop.
through VNC viewer while xNFS mode allows opening applications directly using X-forwarding (e.g., ssh -X). vncNFS and xNFS modes use a VM where we mount the home directory of the host machine to a VM directory and use the mount location (whenever possible) to approximate transparent file system view. Note that, both these modes still use the VM file system for accessing configuration files, application caches, etc. from the VM user’s home directory and system directories. The two qOS modes (qOSL and qOSR) are identical in all aspects but differ in the manner they load application binaries and libraries, where the former loads the binary and libraries from the qVM while the latter loads it from the host. The network interface is assigned to the VMs through VMM bypass [19, 33] for all configurations except NoSec. Additionally, xNFS uses an internal network interface (exposed through VirtIO [55]) for X communication between the VM and the host.

6.1 GUI application overhead

Experiment methodology: We use popular end-user applications thunderbird [63] email client, dillo [17] low footprint web browser, GNU editor (gedit) and PDF viewer for our experiments. One of the challenges in the empirical analysis of GUI application performance is the human factor during the experiments. We use an automated input generation mechanism provided by the Linux kernel community [13] to trigger application actions without any human intervention. For example, to send an email using the thunderbird email client, we generate the key shortcuts and mouse movements required to send an email using an input generation program while the thunderbird application is the active window in the system. We repeated the same key generation pattern after starting the application using different quarantine setups and captured system statistics to analyze their performance comparatively. All GUI experiments were repeated three times, and the average readings are reported.

6.1.1 Email client. For this experiment, we used thunderbird email client configured for an existing account in an email server hosted over LAN containing a huge number of emails (more than 15000). We used three workload profiles for this experiment as shown in Figure 4—(i) open a PDF attachment from an email (OpenAtch), (ii) search a string in the emails (Search), and (iii) send an email to the self account. All these operations are performed through the automated input mechanism explained above. For vncNFS and xNFS modes, we have used the same email account.

As shown in Figure 4, vncNFS results in maximum overhead compared to all other modes—4.5x, 4x and more than 6x compared to NoSec mode for open attachment, search and send email, respectively. In terms of CPU utilization, qOSL performs better than xNFS in open attachment and search workload scenarios by a factor of 1.29x and 1.14x, respectively. CPU utilization for sending an email is better in case of xNFS compared to both qOSL and qOSR by ~1.25x. This can be attributed to excessive I/O event messages (po11) (~30% of total messages) between the Syscall Interceptor (in qVM) and the HostOS Gateway (on host) during email editing. As we have discussed earlier, we have not implemented adaptive select logic for po11 and the po11 performance can be improved by such a design. One more possible factor can be the file I/O activity performed on the host while in case of xNFS, it is performed on the local file system. qOSR results in higher CPU usage by a factor of 1.17x and compared to qOSL for email attachment and search operations. This is primarily due to the increased number of mmap faults in case of qOSR (Table 4) that are handled by performing a fault handling over the communication channel.

6.1.2 Web browser. For this experiment, we used dillo web browser with three different workload profiles. As shown in Figure 5, the workload profiles are: (i) open google search page (NewSite), (ii) open multiple web sites using tabs (MultiSite), and (iii) download a small PDF file of size 300KB (and
Table 4. Breakdown of host operations performed for different application usage scenarios for qOS local and remote modes.

| Workload | Operation          | # of qOS messages | # of mmap messages | # of display I/O messages | # of File I/O messages | I/O event messages |
|----------|--------------------|--------------------|--------------------|---------------------------|------------------------|--------------------|
| Email    | Search (qOSL)      | 6146               | 3                  | 2840                      | 110                    | 2999               |
|          | Search (qOSR)      | 6674               | 495                | 2563                      | 151                    | 2913               |
|          | Send email (qOSL)  | 25787              | 12                 | 9513                      | 3167                   | 9306               |
|          | Send email (qOSR)  | 27457              | 996                | 7908                      | 5444                   | 6801               |
| Web browser | MultiSite (qOSL)   | 8051               | 0                  | 3819                      | 1241                   | 1905               |
|          | MultiSite (qOSR)   | 60452              | 39707              | 3301                      | 2731                   | 1645               |
|          | Download (qOSL)    | 5971               | 0                  | 3454                      | 97                     | 1933               |
|          | Download (qOSR)    | 10751              | 2324               | 3589                      | 407                    | 1992               |
| PDF viewer | Search (qOSL)      | 27210              | 0                  | 5326                      | 16686                  | 5198               |
|          | Search (qOSR)      | 29222              | 119                | 5679                      | 17057                  | 6477               |
| Text editor | NewDoc (qOSL)     | 33102              | 0                  | 16442                     | 16                     | 16403              |
|          | Search (qOSR)      | 34555              | 383                | 17022                     | 279                    | 16113              |

Figure 6. Comparative CPU overhead for PDF viewer (evince) and Text editor (gedit) workloads.

store it on NFS mount for xNFS and vncNFS). For opening a simple web page like google search page, the absolute CPU utilization was very low (between 0.25% to 1%) for all workloads except vncNFS, where the CPU utilization was around 4%. vncNFS results in more than 6x and 8x additional CPU overheads compared to the NoSec system for MultiSite and Download scenarios, respectively. qOSL performs better than xNFS for Download (by 1.2x) while results in additional CPU overheads by a factor of 1.25x for MultiSite scenario. Comparatively, qOSR results in higher overhead in case of MultiSite workload than the Download workload. This can be explained by observing the file I/O activity across the two workload scenarios where with MultiSite, the number of I/O operations are little less than 7 times compared to the Download workload (See Table 4).

6.1.3 PDF viewer and text editor. In Figure 6, we present the performance comparison of two workloads with the following application scenarios. For PDF viewer, we used a 7MB PDF document (on the NFS for xNFS and vncNFS modes) and performed three operations i.e., (i) scroll the PDF file using down arrow (referred as Scroll), (ii) search a frequently appearing key word in the document (Search) and, (iii) perform slide show for 50 pages (SlideShow). To evaluate text editor, we used two workload profiles—search and replace a common keyword from an opened document (referred to as SrchRep) and edit a new document by entering 1000 alphabets and saving it (DocEdit).

As shown in Figure 6, xNFS performs marginally better than qOS for PDF Search while results in significant overheads (around 5x and 2x) compared to the qOS modes for Scroll and Slideshow, respectively. vncNFS results in lower performance overheads in Search operation compared to other operations as the workload CPU usage is primarily due to the application code and file read operations (from the local page cache). Even with the read buffering scheme, the qOS mode performance is still impacted because of heavy file I/O (around 60% operations on the host are file I/O operations as shown in Table 4) can not match the local caching performance achieved because of NFS.

For Text editor workload (gedit t), CPU overhead for vncNFS is significantly higher than the other modes (up to a factor of 15). CPU overheads for all other modes are comparable to the baseline NoSec setup. Interestingly, for editing a new document (DocEdit), the performance of xNFS mode is better than NoSec setup. We observed the same behavior with repeated experiments and found that the Text editor loads some profiles from the local system, and this may be different in the qVM and the host. The performance overhead of qOS modes with DocEdit (by 1.29x more CPU usage compared to NoSec) can be explained by excessive event I/O requests (similar to thunderbird) and display related I/O requests, when added contribute more than 90% of the total requests (Table 4) sent across to the host system.

Summary: The performance of vncNFS is not very promising while xNFS with its limitations results in low performance overheads in all applications except PDF viewer. Between xNFS and qOS, there is no clear winner with respect to resource overheads, better qOS modes are consistent across
applications and offer other advantages as we show in the next subsection.

6.2 Command line application performance

We have used applications of two categories for the following experiments—batch mode network operations like downloading big files, directories and websites, and, interactive operations on a remote shell and text-based browsing.

6.2.1 Batch operations. For batch mode downloads, we download files over network from within the quarantine environment and store the files on the host file system (through NFS for xNFS mode or qOS file system APIs). We used wget to download the kernel source from a local hosting site (shown as FastWeb in Figure 7, speed limit = 10MBytes/sec), download the same kernel source from the Linux kernel repository (shown as SlowWeb, speed limit = 1MByte/sec), crawl and download a local website (referred to as FastSite, speed limit = 10MByte/sec) and crawl a site over internet (referred to as SlowSite, speed limit = 1MByte/sec). Further, in this experiment, we have used scp in quiet mode to download a single large file of size 650MB (workload referred to as BigFile) and a directory containing a C++ source repository of size 370MB (workload referred to as FatDir). Lastly, we used elinks, a text-based web browser to download a single file of size ~160MB.

As shown in Figure 7, VM-based solutions result in a significant CPU overhead (up to 11x) compared to the NoSec system because of the associated virtualization overheads. Note that, as the applications used are not CPU throttling in nature, the download throughput is the same across all the settings for any given workload. qOSL and qOSR reduces the CPU overhead by up to 2.5x compared to that of xNFS. For wget, qOS performs significantly better than xNFS leveraging write buffering feature which hides the performance penalty because of 4096 byte sized writes employed by wget. For scp and elinks, in qOSR mode, the CPU overhead is improved by 1.14x and 1.06x compared to the xNFS mode.

The difference in improvement across wget and these two workloads is primarily because scp and elinks perform application-level write buffering, which improves the performance of NFS backed writes. For the directory transfer workload, qOS modes improve the CPU utilization by a factor of 1.23x compared to xNFS. This can be because of the NFS overheads associated with a lot of meta-data operations for creating files and directories.

To show the system memory utilization during bulk data transfer, we show the incremental memory allocation during the workload execution for scp and elinks. As shown in Figure 8, qOSR, and qOSL consume very little additional memory compared to NoSec mode, while xNFS consumes almost double the amount of memory. This is primarily because of double caching behavior as the data is cached both in the VM (by the NFS client) and the host file system. Note that, in qOS, the disk cache (e.g., page cache, buffer cache, etc.) is maintained only by the host, and there is no penalty for qOS except for a memory-to-memory transfer using the communication channel. While we have not shown here, wget also results in similar memory overheads. However, as shown earlier, the caching can improve the performance, as shown in the case of GUI applications earlier.

6.2.2 Interactive applications. We have used automated key generation feature [13] to evaluate the performance of interactive applications like remote shell (ssh) and text-based web browser (elinks). In the Shell workload, we connected to a remote host from the test machine (for NoSec, qOSL, and qOSR) and from the VM access through SSH from the test machine (for xNFS). The input trail executes some well known UNIX commands on the remote host, followed by the top command. Finally, it opens a file on the remote host using the VI editor and appends 1000 random characters to it. With the elinks browser, we search the meaning of a word in google and navigate to the first result. After that, we open multiple tabs and browse some web sites. System CPU utilization for both the applications during this experiment is shown in Figure 9. The qOS modes perform marginally worse (in some cases) compared to the xNFS mode for SSH.
workload. The CPU utilization in elinks is similar for xNFS, qOSL and qOSR which is worse than the baseline system by ~10% in the worst case.

### 6.3 Application launch time

To evaluate application launch time performance with different setups, we approximate the start-up time of applications as follows. We start the application with some invalid command-line arguments, which results in application exit, almost immediately, giving an estimate of the start-up time for the application. The application launch time using the qOSL, qOSR and xNFS modes is shown in Table 5. We observed that start-up time for qOSL mode is almost the same as xNFS mode, as the binary and libraries are loaded from the qVM. In qOSR mode, the start-up time increases by a significant factor (by up to 6x) primarily due to the overheads of fetching the binaries, library files, etc. from the host system. Nevertheless, the absolute values are very small to be noticed by the end-user.

#### Table 5. Application start time approx. (in milliseconds).

| Application | qOSR | qOSL | xNFS |
|-------------|------|------|------|
| SCP         | 4.6  | 1.8  | 1    |
| Wget        | 15.8 | 3    | 2.2  |
| Elinks      | 24.4 | 5    | 5    |
| Echo        | 56.6 | 9.6  | 10.4 |

### 6.4 Communication Channel Efficacy

To find out the responsiveness of the communication channel, we sent 32-byte messages from the qOS to the split-context on the host which sends a response without any delay. We observed an average response time of ~ 24 microseconds. We found that, interrupt delivery latency and scheduling latency of the split-context are the primary contributors.

To test the scalability of the communication channel, we created an application which forks many child processes, each of which calls `uname` system call in throttle mode for one minute. For this experiment, we modified the `uname` behavior at the system call level to send messages of size 32-bytes to the host through the communication channel and wait for their response. Table 6 shows the number of messages processed by the HostOS Gateway (executed in the split-context) along with average and maximum CPU usage by the split-context during the experiment. We observe that, with increasing number of child processes in the qVM, the split-context can process more messages up to a limit until maximum CPU utilization is reached (for 100 processes).

#### Table 6. Scalability of the split-context on the host.

| #Processes | AverageCPU | MaxCPU | #Messages |
|------------|------------|--------|-----------|
| 1          | 19.56      | 25.0   | 2809204   |
| 2          | 26.06      | 29.3   | 5006289   |
| 8          | 29.49      | 42.7   | 5386756   |
| 16         | 47.29      | 57.4   | 646970    |
| 32         | 60.51      | 70.0   | 7565041   |
| 64         | 65.95      | 79.3   | 7990928   |
| 100        | 72.38      | 100.0  | 8173783   |
| 128        | 67.09      | 78.6   | 8164545   |

### 7 Discussion

We reflect upon our experience building qOS, discuss some of the issues which we encountered and possible ways to tackle them as part of the future work.

**Scalable I/O handling:** The design choice of a fixed 1:M mapping between the host split-context and the processes of split-application is primarily to handle denial of service attacks like fork bomb. However, this can become a bottleneck and result in responsiveness issues. For `select` and `poll` with file handles spanning across guest OS and the host OS, any time-slice juggling based solution is required to quickly adapt to strike a balance between the CPU overheads and the responsiveness. A more attractive alternative can be to adaptively change the number of split-contexts on the host to address both security and efficiency concerns.

**Measuring responsiveness:** One of the important aspects of GUI applications is responsiveness. From our experience of experimenting with different GUI applications, we could feel a very good user experience with qOS systems. Nevertheless, we can adopt techniques like Deskbench [24] to empirically analyze the responsiveness of qOS, xNFS and uncNFS.
Network access from host: In qOS, the network device is hosted in the qVM. Therefore, if the machine does not have multiple interfaces or SRIOV like support, the challenge is to provide connectivity to the host in a secure manner. Techniques like iKernel [62] provide a method for creating host network devices through the VM using shared memory channels. This can be easily integrated into qOS as the shared channel is an integral part of qOS.

qOS and VMI: The overall security of qOS can be further improved by incorporating VMI techniques [52, 66]. In qOS, the shortcomings of black-box VMI can be addressed by providing useful guest OS statistics and profiling information through the qAgent. We believe this direction has a lot of potential and should be explored in a comprehensive manner.

8 Related Work

Control hijacking is used to exploit vulnerabilities in code and gain control over a victim’s machine. Attacks like buffer overflow [44], ROP [10], JOP [8], CAIN [6] etc. exploit control flow integrity vulnerabilities. Similarly, techniques like data execution prevention (DEP) [40], StackGuard [15], ROPecker [11] and ASLR [34, 57] try to provide better defense against these attacks. However, all the defense techniques assume that the administrator be knowledgeable and careful while changing the system configurations. qOS complements these defenses by addressing the security issues of gullible users.

Another line of defense is to execute potentially harmful applications in a restricted environment (a.k.a. sandbox). MiniBox [31] and MBOX [25] are sandbox techniques to protect the OS and malicious applications from each other. MBOX implements a sandbox file system layer above the host file system to monitor and restrict modifications to the host FS by suspicious applications. Systrace [50] and gVisor [1, 69] use system call restriction policies. Proxos [61] proposes a system similar to qOS to address the problem of securing applications from malicious OSes by executing security-critical applications in a sandbox. The qOS approach differs as we execute potential entry point applications in the quarantine and restrict access to files created by the potential entry point applications. Several previous works like Drawbridge [49], Graphene [64] and Xax [20] extend the library OS techniques to provide isolation across application with transparent display. However, unlike qOS, they lack the file system transparency in favor of better isolation. Bromium-HP Sure Click [12] is an enterprise solution which executes chromium browser in a micro-VM, hosts all downloaded files in the VM file system and the user accesses them through the browser. While Bromium only cocoons the chromium browser and some file types (like PDF), qOS is a generic design to quarantine any application and files type.

To monitor and protect the guest OS, researchers have proposed several techniques at the hypervisor level. SecVisor [56] monitors changes to the MMU and IOMMU to enforce user-generated policy and protect the kernel from modifications by any malicious DMA writes. Nickle [53] protects the kernel memory from malicious code using a shadow copy of the guest kernel. qOS complements the above techniques. Virtualization is also used to isolate buggy and vulnerable device drivers. LeVassuer et al. [30] and iKernel [62] propose techniques to efficiently isolate device drivers using VMs to contain driver bugs and enhance system security. Techniques like iKernel can be useful for qOS system (§7).

Apart from monitoring, virtualization has been used to isolate security-sensitive applications and the OS using virtual machines (e.g., Terra [21]). TrustVisor [38] and Flicker [39] combine virtualization techniques with hardware support to improve operating system security. Responsiveness of remote desktop mechanisms can be improved by coupling them with software like VMGL [28]. VMGL improves the rendering capabilities of X11 and VNC based system by leveraging hardware rendering acceleration. qOS can take advantage of such hardware features because of its split-design while providing improved security at the same time.

9 Conclusion

In this paper, we proposed an end-to-end implementation and evaluation of qOS, a generic and user-transparent solution to improve the security of unwary users by leveraging virtualization techniques. Compared to straw man solutions like xNFS and oncNFS, qOS provides improved security and efficiency in terms of CPU and memory usage. Further, qOS is flexible enough to incorporate application-specific optimizations. We demonstrated some common desktop applications to be working seamlessly with qOS providing user experience similar to a native system. The empirical evaluation of qOS shows promising results by improving the performance in orders of magnitude compared to the existing solutions. qOS can complement existing security techniques like VMI to attain higher levels of security for end-user devices.

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