

Performance and Quality of Experience of Remote Access Laboratories

Alexander A. Kist and Andrew Maxwell

Faculty of Engineering and Surveying
University of Southern Queensland
Toowoomba, Australia
kist@ieee.org, maxwella@usq.edu.au

Abstract—Remote Access Laboratories have become important learning and teaching tools. This research presents a performance study that targets a specific remote-access architecture in a university environment. The system provides authenticated and mediated global remote access to virtual machines as well as hardware systems, which drive physical experiments. This paper presents system performance results that have been obtained with a set of automated and user-based tests. Key aims of the study were: To gain a better understanding of traffic that is caused by experiment usage; to get an indication of expected user performance; and to develop a measure to predict Quality of Experience, based on easily measurable Quality of Service parameters. The study emulates access bandwidth, round trip times of typical usage scenarios and provides results that allow classifying expected user performance. It demonstrates that failure rate is excellent measure of usability. Thin-client and remote desktop architectures are popular to separate the location of users and the actual data processing and use similar structures. Results of this study can be applied to these applications as well.

Index Terms—remote access laboratory; performance evaluation; Quality of Experience (QoE)

I. INTRODUCTION

Many modern learning tools rely on computers and the Internet. The work presented in this paper is motivated by a Remote Access Laboratory (RAL) environment that has been developed at the University of Southern Queensland [1]. As the university is a distance education provider, approximately 80% of the students are located off-campus. To give these students access to practical learning experiences similar to those of their on-campus peers, RAL project was devised. The aim of this initiative was to provide remote access to video-supported laboratory experimentation. This allows students to undertake contextual action-oriented learning. This is particularly important as laboratory activities and practical exercises form an integral part of programs in many disciplines, and are necessary for program accreditation.

RAL enables authenticated and mediated access to computer systems. The system is accessible via the Internet. Two types of activities can be hosted: software experiments and hardware experiments. Software experiments are generally hosted on virtual machines in the local data center; hardware

experiments are implemented as computer controlled rigs. Access is provided by remote desktop control. Two main components make up the system: a remote desktop application, and a management and booking subsystem facilitating experiments access. The system also integrates with the Learning Management System (LMS). In terms of technical performance, only the remote desktop solution is important.

An increasing number of other scenarios exist where applications that use remote desktop access are relevant. This includes thin-client solutions. Essentially both use the same technology. User inputs such as keystrokes and mouse moves are transmitted to a server, display information is returned to the local device. Program code of applications and the operating system are executed on the server. Either software clients running on a personal computer, or thin-clients, which are low-cost computers that mainly provide a display and handle user inputs, are used as clients. A number of alternative desktop/application access options are widely in use. These include Citrix Presentation Server [2], Windows Remote Desktop Protocol (RDP) [3] and Virtual Network Computing (VNC) [4].

Network parameters such as available data rate and RTT have a major impact on the usability of these tools. This is particularly relevant if these systems are providing off-site access. The bottleneck of the connection will be generally in network located off-campus. The focus of this study is therefore on the impact of Wide Area Network (WAN) performance on the RAL system. Quality of Experience is discussed in technical literature as a parameter that captures user expectations of a system. Besides a growing interest there is no universal definition of QoE available. Most studies take a network service provider perspective, e.g., investigate what service levels are required to satisfy customer expectations. To overcome this bias, [5] has defined a frame with specific performance measures and looks at quality of experience and performance from an application users' perspective, e.g., focus on usability – in what location and under what conditions is an application or service usable. In the context of learning systems, the situation becomes more difficult as QoE becomes the Quality of Learning Experience (QoLE).

The aim of this study is threefold: To develop a methodology that allows the performance evaluation of Internet access, to get a better understanding of traffic that is

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caused by particular experiments, and to get an indication of expected user performance. The intention is to measure basic network parameters and to be able to predict the usability of an experiment. This information then allows determining what Internet access options are required (e.g., access bandwidth) and what geographic locations can be supported (latency). The paper presents traffic profiles and initial usability results.

The remainder of this paper is organized as follows: Section II discusses related work, Section III introduces the test environment and Section IV describes the methodology that has been used for measurements. Section V summarizes the results of this study and Section VI concludes this work.

II. RELATED WORK

One of the key applications of remote desktop architectures is to provide remote access to office applications. This includes thin-client based applications as well as off-site desktop access. There have been a number of studies that have analyzed the performance of thin clients. A performance study of Windows-based thin-client architectures is presented by [6]. The study reports that QoE for Microsoft Office applications using Citrix and RDP is comparable under normal network conditions. For applications with increased RTT and packet loss, RDP outperforms Citrix.

Tolia et al. [7] investigates interactive user experience on thin clients and reports that “thin-client computing is highly variable and depends on both the application and available network quality.” The study used both measurements and simulations and stresses that latency is the key limiting factor and not bandwidth. Lai and Nieh [8] evaluate in a comprehensive study thin-client performance over WAN networks and specifically Internet2. The study reports major differences in performance between various platforms. It also identifies latency as a key performance factor. Yang et al. [9] addresses user perceived performance in benchmarking for thin-client platforms. The study uses “slow-motion benchmarking” that correlates network traffic and user actions to predict performance of thin-client platforms. This study focuses on the performance and QoE of SGD in response to changing network conditions.

QoE has increasingly become a focus of networking and computer research. Technical disciplines generally relate QoE to measures of to the Mean Opinion Scores (MOS) [10] of a user population. Such measures have been widely used in telephony systems. Other disciplines generally include personal factors as well. “Quality of experience” becomes a more inclusive term and goes well beyond the perception of the experience of a particular service. In psychology, for example, quality of experience includes the effect of motivation on achievement related emotions, satisfaction and attitudes [11].

Both standardization bodies such as the ITU-T [12] as the research community have proposed diverse definitions for QoE. In this research project “QoE is a measure of user performance based on objective and subjective psychological measures using a service or product to achieve a particular task or objective.” as proposed by [5]; an extension of the definition by Brooks and Hestnes [13, p. 12]. In the context of Internet applications, QoE has been discussed by a number of

researchers. Kuipers et al. [14], for example, discusses ways to measure QoE. Martinez-Yelm et al. [15] consider “How QoE can be measured and how the district layer in a networking environment can influence (...) perceived QoE.”

Both research community and industry are working on ways to qualify and quantify mapping between Quality of Service (QoS) and Quality of Experience. One-dimensional examples include [16] that propose an exponential relationship between QoS and QoE; and [17] that shows that experience and satisfaction follow logarithmic laws. A number of authors also propose multi-facet QoE constructs such as [18] or [13] that take multiple factors into account. Most research does not explicitly account for the relationship between QoE and the task that is performed, i.e., experience relates to tasks; tasks involves one or more applications; and the applications rely on network connectivity to operate.

The framework introduced in [5] proposed a number of specific performance parameters such as objective Quality of Application (oQoA), i.e., application performance; and objective Quality of Use (oQoU), i.e., fitness for a purpose, to overcome the limitations of a general QoE definition in evaluating the usability of an application or service in an online environment. This paper focuses on two aspects, the subjective Quality of Application, i.e., the Mean Opinion Score; and the objective Quality of Use, i.e., is an experiment *fit for purpose*. In the context of this work, “fit for purpose” is defined as the ability to successfully undertake and complete an online activity with specific tasks and outcomes.

This is particularly relevant in the context of teaching systems as QoE becomes Quality of Learning Experience [19]. There is a distinct difference between attempting to successfully complete a task and undertaking a learning activity. The extensive literature on online learning suggests that many other factors such pedagogy and learning tool design have a significant impact on learning in online environments [20]. Sambrook’s [21] study, for example, shows that user-friendliness, presentation, structure of tasks and navigation within tasks can affect the quality of online learning tools. Basic strategies such as a clear set of instructional goals, the perceived relevance of tasks in relation to these goals and the resultant motivation and cognitive processes of learners, are fundamental to how learners behave and perform in any learning environment [22], [23].

Some factors, such as system performance are limited to interactive online environments. Moebs’ [24] focused on the effect of ‘flow’ on QoE for learners, in an attempt to address this. Network access quality is a necessary but not a sufficient condition to provide access to online learning tools in the context of distance education. For the outcomes of this paper, the absolute value is not important, but that a threshold exists that marks a minimal quality level. Gilbert et al. [25] support this assumption. The authors suggest that network related technical performance of learning systems is not relevant as long as the service is satisfactory and traditional learning design factors are dominant. However, as soon as there are disruptions, they become a concern.

Another aspect is that learning tools might not be perceived as such [26] and this impacts on performance expectations. It is

also important to note that the nature of these relationships is service (learning tool) and task specific. It is obvious in this context, that the performance study introduced in this paper only marks an initial millstone in an attempt to understand the QoLE of RAL learning activities.

III. TEST ENVIRONMENT

For system design and evaluation, it is important to be able to emulate the experience of off-site external students. Tests undertaken as part of this study use the active system and the active campus network. Fig. 1 depicts an overview of the environment. Users, depicted on the right, access software and hardware experiments, depicted on the left. In between, from the right to the left, the RAL system, campus network and WAN emulator are depicted. The two branches in the dashed boxes indicate the test environment and live user access.

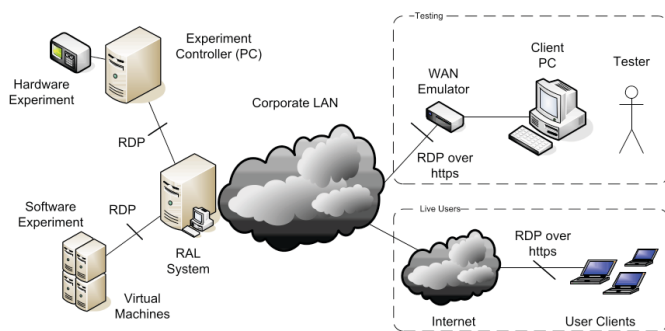


Figure 1. RAL test environment.

A. Desktop Test System

Testers use standard issue Dell Optiplex Desktops, with 4GB memory, running Windows XP, service pack 2. Firefox 3 is used as a web browser. Clients connect via 100Mbit Ethernet to the WAN Emulator. Test scripts that emulate various user workflows are executed on these systems.

B. WAN Emulator

The WAN emulator implemented in an embedded Linux system with multiple Ethernet interfaces. It features a VIA Nehemiah processor, 1GB memory and runs Gentoo Linux, kernel 2.6.32. NetEm [27] is used to emulate network the various network conditions including different delays and bandwidth limitations. It is part of the Linux kernel traffic control facility and allows emulating delay and packet loss. All transit traffic is captured during a test using tcpdump. Wireshark is used for high-level traffic trace analysis. Traffic management at line speed is supported by this unit, CPU utilization remained well below 5% during tests. The emulator is placed in-between the user workstation and the corporate network. Testers can configure network conditions with a simple web interface. Survey data to record the subjective experience of the test subjects is also collected via the web interface.

C. Campus Network

The RAL system is hosted in a data center; client and WAN emulator are located in an office. No dedicated link between WAN Emulator and RAL System exists. Instead the campus network, the cloud in Fig. 1, provides connectivity. This is not seen as a major impairment for this study, as the key focus is performance and user experience on WAN networks and the Internet. Parameters that influence performance, such as Round Trip Time (RTT) and throughput are at least a magnitude better in the local network. RTTs on campus, for example, are typically below 1ms. From most locations that are not connected to Australia's Academic and Research Network (AARNet) [28], RTT are at least 30ms. A similar situation applies to throughput. On campus, bandwidth is at least 100Mbit/s, most households have practical access speeds of well below 10Mbit/s.

D. RAL System

The RAL architecture consists of two key components: the management system, implemented in PHP/MySQL, hosted on an apache web server and Oracle's (previously Sun's) Virtual Desktop Infrastructure 3.1 (VDI). VDI itself is made up of four layers. On the he Desktop Access Layer a web browser uses Sun Secure Global Desktop (SGD) Software to initiate a virtual desktop session. The Session Management layer, the central component of this architect, uses RDP redirection to establish a connection to a virtual or real system via RDP. The RAL system is not a dedicated test setup, but the current system also used with live students and classes. This is largely due to complexity of the system and limited resources to duplicate the configuration for this study.

E. RAL Experiments

Experiment can be software only, or require hardware rigs. Both are driven via a graphical user interface, usually Windows XP. For this study a software experiment has been chosen. Ubuntu 9.10 is hosted on a virtual machine. The activity includes a shell scripting exercise and control of a web-relay on the local network. The main aim of this activity is to expose students to shell scripting and the control of a relay via a network connection without the need to install a Linux distribution on their own computers and to purchase the hardware.

IV. METHODOLOGY

This section introduces the test and evaluation methodology used in this study. The tests target three areas: objective scripted episodes, test by individuals to establish if an application is fit for a purpose and a questionnaire to evaluate the user perception of the service.

To produce objective performance results, a number of tasks are scripted. Under Windows, the AutoHotkey tool [29] can be used to reproduce the same keystrokes and mouse moves for all tests. This open source tool can be used to check for changes to the display, either by checking individual pixels or match screen images. The script performs a task and then waits for the screen to change. Using this technique, runtimes can easily be measured. Tests and scripts are specific to

experiments being trialed. For the Linux experiment, discussed in Section III(E), the following tasks are executed: open a terminal, delete the old script file, open a text editor, type an 8 line script, save the file, close the text editor, make the file executable, open a web browser to display a webcam (640x480 pixels, 1 fps, MJPG) which points to the web controlled relay, run the script and verify that an LED turns on and off. These activities represent typical actions that have to be executed to drive the experiment. The same sequence was used for scripted (automated) tests as well as tests with individuals.

To make the test environment more accessible to the test subject, network parameters are related to practical access options and locations. The following locations and associated RTT were selected as typical locations for potential system users: Local – Toowoomba (<1ms), Melbourne (50ms), Perth/New Zealand (100ms), Singapore/USA (200ms), Europe/Dubai (300ms) and other locations. These are only indicative values; in practice, RTT largely depends on routes packets take to their destination and routes depends on Internet Service Providers (ISP) and peering arrangements. In a related research project, network performance at various student locations will be sampled. For these initial investigations a low delay variation of 2% jitter has been imposed on the RTTs, further tests will evaluate the impact of jitter in more detail.

Broadband access options in Australia vary greatly and depend on the type of access and location, i.e., generally ADSL or wireless broadband access in metro areas, wireless broadband in fringe and rural areas and satellite access in some fringe and rural as well as remote areas. Bandwidth changes with evolving technology (e.g., ADSL, ADSL2+) and it is expected that the Australian National Broadband Network initiative will have a major impact on access bandwidth in the near future [30].

Whereas bandwidth is an important factor for many services and applications, in the context of RAL and remote desktop access, it defines a threshold rather than a parameter that has a variable impact on performance, i.e., either the bandwidth is sufficient or not. Additional bandwidth does generally not improve the performance. It is therefore enough to provide the amount of bandwidth that is required to undertake a particular activity from a QoE perspective.

To evaluate the impact of limitations of diverse Internet access options, tests have to be performed. This study focuses on two aspects, subjective QoA (MOS), i.e., the user perception of an activity and the objective QoU, i.e., if the activity is fit for a purpose. The latter will be evaluated by tests with individuals as well as automated tests. For this particular application, subjective QoA tests do not allow conclusions about usability as demonstrated in [5]. Tests with humans are a valuable, but more difficult to arrange than automated tests. However, these are necessary to provide a perspective for automated test and to develop a relationship between QoS and QoE in the context of remote laboratories. Testers performed the same tasks as for the automated tests and their completion their task completion time was recorded. They were also asked to rank their experience and their subjective impressions were recorded by a questionnaire after each test.

This section discusses measurement results in detail. The analysis focuses on upstream and downstream RDP traffic. As SGD uses https access all transmitted traffic is encrypted. Two aspects are evaluated: bandwidth usage and QoE performance measures.

A. Bandwidth Usage

The purpose of the bandwidth measurements is to put the performance results into perspective and highlight the traffic that is caused by undertaking the experiment. The focus is bandwidth and traffic that can be observed if no throttling is in place. For all tests described in this subsection, WAN emulator features are disabled, i.e., local area network performance is measured.

Fig. 2 depicts three consecutive runs of the scripting test. Each test takes approximately 100 seconds. The graph shows measurements for one-second intervals. Upstream traffic encodes keystrokes and mouse moves, downstream traffic consists of screen updates. The average rate fluctuates around 10kbps for a 10-second moving average downstream for the script typing and related screen updates. For major screen updates, such as opening a shell, the 10-second average rate is around 50kbps. Once the MPJEG stream is active, the 10-second moving average rate rises to approximately 5000kbps.

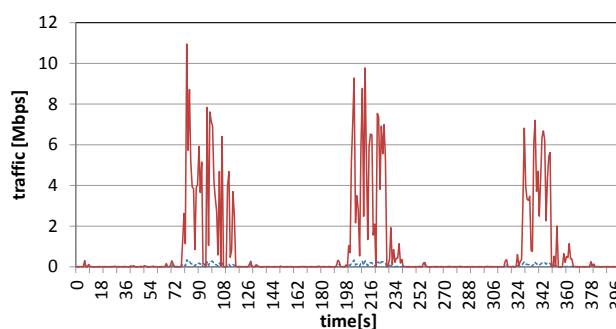


Figure 2. Shell scripting, traffic upstream (dashed) and downstream (full).

This demonstrates the large impact the video stream has in the virtual environment. If the MJPG stream is transmitted separately, i.e., directly to a browser at the remote end, the traffic can be reduced considerably, in this example by a factor of 25. Displaying the MJPG stream directly at the client limits the requirements to average rate of the actual MJPEG stream, which is only 200 kbps. These results are not surprising, but it demonstrates the advantages a direct webcam feed has for this particular application. This is relevant as webcams are a key feature of most physical experiments. Several measurements with limited access bandwidth demonstrate, that the impact of available network bandwidth directly relates to the requirements of the activity. The threshold requirement is at the level identified in the trace; for example depicted in Fig. 2, 5000 kbps with video via RDP or approx. 200kbps with a separate video feed. If the necessary bandwidth is available, bandwidth has no impact on the usability or QoE of the activity; the critical parameter becomes latency, discussed in

the following subsection. These results agree with the observations by Tolia et al. [7] and Lai and Nieh [8].

B. QoE and Latency

This section discusses the impact of variations in network latency. The tests were undertaken in the environment discussed in Section III for the Linux shell scripting exercise. Four results are presented: the average time it took to complete the scripts for automated tests, the failure rate of automated tests, the relative changes in completion time for user-based tests and the average MOS values for user based tests. The first graph in Fig. 3 depicts objective QoU parameters for the automated scripting activity. It shows duration and failure rate versus RTT, imposed by the WAN emulator. The bars indicate 95% confidence intervals. The failure rate was calculated by identifying errors in the test script execution. If errors were detected, the test was terminated. Errors were generally caused by missed keystrokes, hung keys or lost mouse clicks. Both test duration and variability of the duration are increasing with longer RTT. However, there is no indication at what latency the usability of the activity is affected. The duration or variability of the automated tests does enable conclusions on usability of the activity.

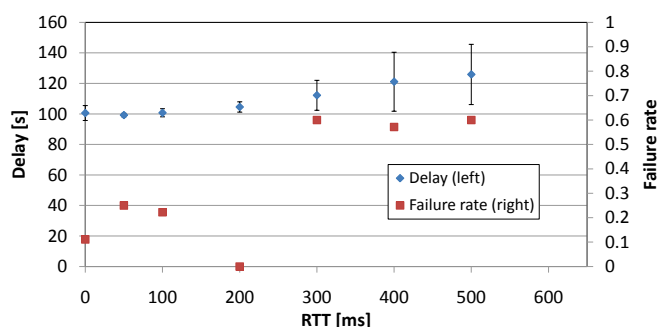


Figure 3. Automated tests: Average script test duration and failure rate versus RTT.

Failure rate, on the other hand, shows a pronounced step change between 200ms and 300ms. Lost keys are not a real issue for human testers; however, the following tests with individuals demonstrate that the increased RTT also causes issues for human users at the same margin.

In the next step a number of human subjects undertook the scripting exercise. With each test iteration latency was increased. Fig. 4 depicts the relative difference of individual results versus the RTT. This normalization was necessary as the test duration varied considerably for subjects, between two and ten minutes per test. For each subject the average duration of all runs and the relative difference between the test runs was calculated. For a RTT below 300ms, test duration is determined by skill and ability. The first run took the longest for most subjects, as they were not familiar with the activity. In the second and third attempts, performance increased. Only one test subject was determined enough to finish the test for a RTT of 500ms. As for the automated tests, duration is not a good measure for usability of the system.

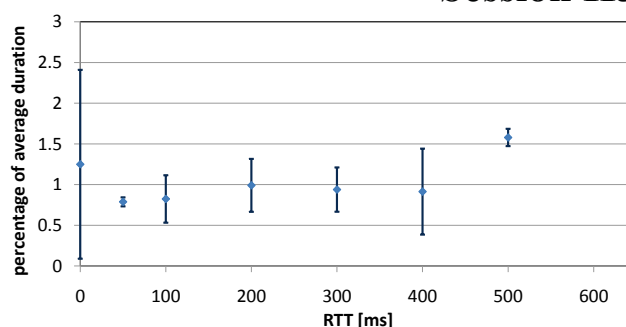


Figure 4. User tests: Percentage of average test duration versus RTT.

After each iteration the test subjects were asked to rate the (technical) quality of the remote access session according to their perceived impairment using the following qualifiers: Imperceptible (Excellent, 5), perceptible but not annoying (Good, 4), slightly annoying (Fair, 3), annoying (Poor, 2) and very annoying (Bad, 1). Corresponding quality perception and MOS scores are given in brackets. Fig. 5 depicts the corresponding MOS scores and 95% confidence intervals for the tests. These correspond closely to the failure rates in the automated tests. All test subjects did not believe that the activity was usable with RTT above 400ms: “There seems to be little difference between these last few tests, being 400, 500, and 600ms. Seems once you hit this significant delay range, it’s all pretty much the same.” Most testers agreed that above 200ms, the activity becomes practically unusable. At 300ms lost and duplicated keys, as well as keyboard lag cause frustration. These results are independent of the access bandwidth and are particularly relevant as it limits the geographical reach of the RAL system to Australia and close neighbors.

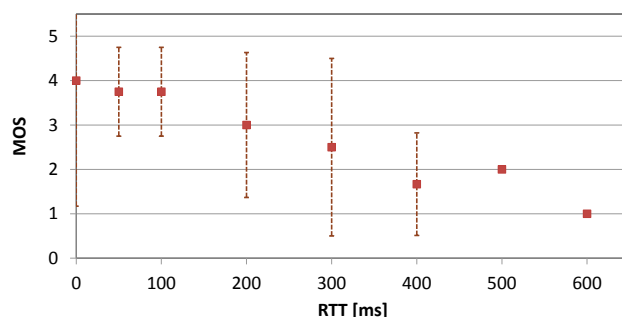


Figure 5. User tests: MOS versus RTT.

VI. CONCLUSION

This study has introduced a performance analysis of Remote Access Laboratories in terms of access network limitations. Traffic analyses have shown that bandwidth requirements for basic tasks such as shell scripting and web browsing have moderate bandwidth requirements. Traces for webcam streams have shown that access via RDP caused traffic by a factor 25 larger than direct http access to the video stream. Streaming video within remote desktop should therefore be avoided. Bandwidth requirements are largely

experiment, i.e., activity, specific. These can be evaluated and optimized on an activity basis.

As has been reported by other studies, it has been verified that RTT is the most important performance factor. Increasing RTTs lead to increased response times, which in turn result in a sluggish user experience. The overall framework for testing can be applied to other applications and results are applicable to other systems using SGD to provide thin-client or remote desktop access. The results restrict the use of interactive remote access to limited geographical region. If users are located further away, alternative options to RAL are necessary. RAL access via geostationary satellites is also not feasible due to the high latency.

The study has demonstrated duration of automated tests as well as the relative increase in duration for tests with individuals provides no measures that allow a judgment on the usability of a service or experiment. Failure rate for automated tests and the ability to successfully complete individual tests, on the other hand, are objective measures to determine if a service is fit for a purpose; the most important factor for remote experiment access.

The literal Quality of Experience, i.e., Quality of Learning Experience, has not directly been discussed in this paper; however, initial results of a related study show that the learning experience is largely determined by other factors such as the quality of design and delivery of the activity. As long as an experiment or service is usable, the impact of reduced technical performance on the quality of the learning experience is minimal. The study in this paper has demonstrated that usability thresholds could be identified by both the user-based as well as the automated tests. Intuitively, failure rate and MOS values are related as lost mouse clicks and keystrokes also introduce a level of annoyance for users. Future work will investigate and model this relationship in more detail.

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