Quality of Experience in Remote Virtual Desktop Services

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***Abstract*—Remote Virtual Desktop (RVD) services provide flexible and cost-effective means to deliver virtual PCs to end-users. RVD services have been traditionally deployed in enterprise LAN scenarios, where network performance is optimal and the Quality of Experience (QoE) undergone by its users is generally not an issue. However, the need for mobility of RVD users (e.g., remote office, home office, etc.) and the explosion of Cloud-based services have pushed RVD to WAN scenarios, and nowadays it is common to find RVD services running at large datacenters in the Cloud. In such a context, network delay and bandwidth are very dynamic and difficult to guarantee or even to control, and QoE becomes a real bottleneck. In this paper we present a complete study of the QoE undergone by 52 RVD users in controlled subjective lab tests. The study is performed on a dedicated RVD testbed based on Citrix technology, which is the de-facto RVD solution used in enterprise scenarios. The study permits to better understand the interplays between network performance (i.e., network delay and bandwidth) and QoE in RVD services. In addition, it provides interesting results on the behavior of RVD users when confronted to variable network conditions w.r.t. their behavior on standard local desktops.**

Keywords—Remote Virtual Desktop; Citrix; Quality of Experience; Lab Tests; MOS; Acceptability; Productivity.

I. Introduction

The Remote Desktop (RD) paradigm allows end-users to remotely access content and applications running on their PCs through a network connection. When those PCs are provisioned through a virtual machine manager or *hypervisor*, RD turns into the Remote Virtual Desktop (RVD) paradigm. In RVD the virtual PC is rendered by a remote RVD server, and the end-user only requires a device with displaying capabilities (e.g., a physical PC, a tablet, a smartphone, etc.), a piece of software called the *thin-client*, and a network connection to access the PC desktop from any remote location.

RVD services have been traditionally deployed in enterprise LAN scenarios, where network performance is optimal and the Quality of Experience (QoE) undergone by its users is generally not an issue. The need for mobility of RVD users and the explosion of Cloud-based services have pushed RVD to WAN scenarios, and the current trend is to move RVD services to large datacenters in the Cloud; EyeOS, CloudMyOffice, and CloudTop are some examples of this emerging trend. The key benefits of hosting RVD services in remote datacenters rely on the flexibility of maintenance, the elasticity of resources, and the reduction of costs among others. However, moving RVD to WAN scenarios poses a major problem regarding the QoE undergone by the end-users, as network delay and bandwidth become dynamic and scarce and it is difficult to guarantee minimal performance levels to achieve the high performance generally attained in LAN scenarios.

Migrating traditional services to the Cloud has motivated the emergence of a novel networking domain in recent years, namely the *Cloud QoE* domain [9]. Some concrete Cloud QoE studies have been recently conducted [10], [11], shedding light on the complex interplays between network QoS and QoE in cloud services. Our paper provides results in exactly this direction, for the specific case of RVD services.

The key to user satisfaction and good QoE in an interactive RVD session is low response time of the system. In a standard PC, tablet, or smartphone, user inputs such as key strokes, mouse clicks or screen touches are directly processed by the device, and the screen is rapidly updated. In the case of RVD, the user inputs are transmitted from the thin-client to the remote server through the network, the inputs are processed in the server, and the screen updates are sent back through the network to the thin-client, where they are finally displayed. The responsiveness of the complete system depends therefore both on the responsiveness of the RVD system (i.e., remote server and thin-client) and on the responsiveness of the network. In addition, the impacts of the network on the QoE undergone by the end-user depends on the specific activity performed. For example, reading a plain document without requiring screen scrolling or writing an email will generally be less sensitive to large delays and low bandwidth than browsing web pages with multimedia content.

Given the wide deployment and usage of RVD services in WAN enterprise scenarios and the trend of service migration to the Clouds, we are interested in studying and understanding the interplays between network performance (i.e., network delay and bandwidth) and QoE in RVD services. The standard approach to analyze the QoE of a system such as RVD is to conduct subjective lab experiments [1]–[3]. The key benefits of such an approach rely on the participation of real end-users and on the full control the experimenter has on the overall evaluation process, providing as such tangible and solid results. In this paper we present a complete study of the QoE undergone by 52 RVD users in controlled subjective lab tests. The study is performed on a dedicated RVD testbed based on Citrix technology, which is the de-facto RVD solution used in enterprise scenarios. More precisely, we use XenServer and XenDesktop with High Definition user eXperience (HDX) technology for virtualization and desktop provisioning, and a standard Citrix client as thin-client. The tests consider the evaluation of the QoE undergone by the participants while remotely accessing different applications on a standard Microsoft Windows 7 desktop through a controlled network link.

To emulate different network conditions and different access technologies, up-link and down-link traffic is independently shaped using a tailored Linux-based traffic emulator.

The remainder of the paper is organized as follows: section II presents an overview of the related work on Remote Desktop evaluation and QoE. Section III describes the evaluation methodology and the experimental setup employed in the study. Section IV presents the main results of the study, including (i) the characterization of the network traffic generated by the Citrix-based RVD system, (ii) the overall quality and the service acceptability as declared by the 52 participants, and (iii) a behavioral analysis on the performance of the participants when confronted to changing network conditions. Finally, section V concludes this work.

II. Related Work

Multiple papers have previously address the performance of RD systems in WAN scenarios [4]–[7]. However, non of them has conducted extensive subjective lab studies to provide ground results on the QoE offered by such RD systems under changing network conditions in WAN scenarios. In [4], authors study the response time of a VNC RD system for different desktop applications such as text editors, presentation creators, and image processing tools. Authors use a packet traces driven NS-2 simulator for their study, where RTT is varied to achieve the different response times of the system. Their main finding is that the response time of more interactive applications is more sensitive to network delays. In [5], authors deeply analyze and compare several RD systems in terms of consumed bandwidth and latency in LAN and WAN scenarios, using a specific benchmarking technique. Their main finding is that network delay is the key network parameter to optimize when using RD systems in WAN scenarios. Authors in [6] follow a similar approach to previous papers, specifically considering a Citrix-based RD system. Finally, authors in [7] focus their study on the classification of the applications running on a RDP RD system, further applying the results of some subjective tests to decide whether the offered QoE is good or not for the specific application. Unfortunately, the QoE study is omitted in their work and only some very generic results are presented.

An exception to this lack of QoE results in RD systems through subjective tests is [8], where authors address the problem of mapping network performance features such as packet loss and network delay into QoE values. However, the overall subjective tests performed in the study are very limited in terms of test duration (e.g., 10 minutes to test 3 different applications) and ranges of the network parameters tested, limiting as such the applicability of the obtained results. Besides, the focus of the study is exactly the same as that presented in [6], and the QoE analysis is a very marginal part of their study, which is slightly presented at the end of the paper.

The main contributions of our paper rely on performing extensive subjective tests with a fully deployed RVD Citrix system, considering four different desktop applications which are representative of the standard tasks performed in an enterprise desktop. Our study is solid in terms of the quality of the subjective tests and the extension of the obtained results, considering not only the QoE undergone by the end-users in terms of overall satisfaction, but also in terms of service acceptability and behavioral analysis. As such, our work provides solid results not available in previous studies showing the interplays between network performance and QoE in RVD systems.

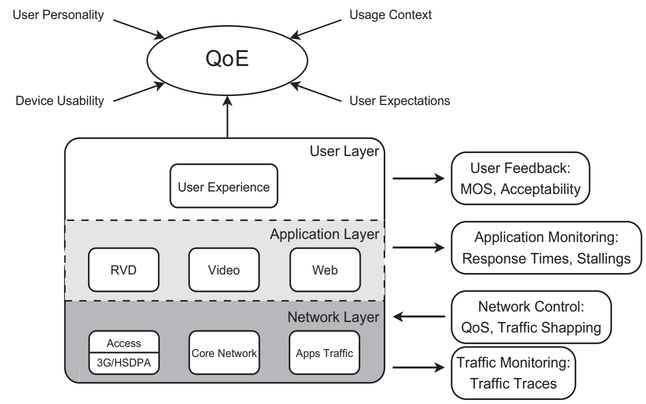


Fig. 1. Layered QoE evaluation methodology for networking applications.

III. Experimental Methodology

The RVD QoE study is realized through the layered evaluation methodology depicted in figure 1. In general terms, the experience of a user with any application is conditioned by multiple influence parameters, including dimensions such as technical characteristics of the application, user personality and expectations, user demographics, device usability, and usage context among others. Particularly when evaluating networking-based applications such as RVD, the influence of the network and its interplays with the particular application have to be linked to the user's opinions, additionally identifying those perceivable performance parameters that are most relevant to the user experience. This mapping is realized by analyzing and correlating the three layers depicted in figure 1: the *network layer* accounts for the influence of the network QoS parameters (e.g., network bandwidth, RTT, etc.); the *application layer* considers both the technical characteristics (e.g., screen compression rate, color depth, etc.) and the perceivable performance parameters of the application (e.g., response times, video stallings, etc.); finally, the *user layer* spans the user subjective opinions on the evaluated application (e.g., MOS values, acceptability, etc.). The experimental evaluation conducted in this work was designed in such a way that all the three aforementioned layers could be properly measured.

The experimental subjective tests consisted of 52 participants interacting with a Windows 7 RVD, provided by a Citrix XenServer on a standard laptop used as end device. Participants were instructed to evaluate four different desktop tasks which cover the most common desktop activities in enterprise scenarios: **text typing**, **screen scrolling**, **drag & drop** of images, and **menu browsing**. The text typing task consisted in writing a short text on a text processor. For the additional 3 tasks, tests were designed so as to avoid user annoyance by the repeatability of the activities, using a *gamification* approach: the scrolling task consisted in reading a web article and answering some associated questions, which required the participant to scroll down the screen to find

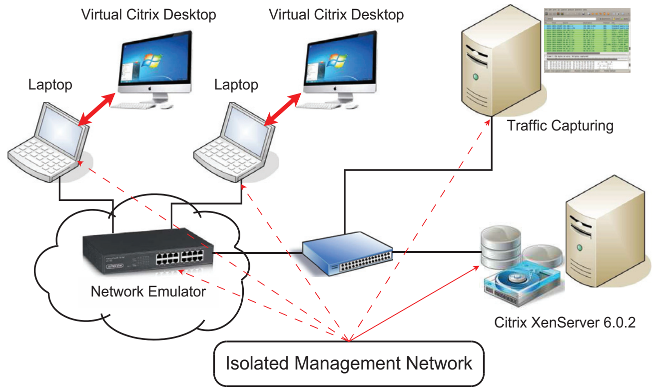


Fig. 2. Experimental testbed for subjective QoE testing of Citrix RVD.

the answers; the drag & drop task consisted in assembling a puzzle with changing images; finally, the menu browsing task was realized through a quiz game, where participants had to select the correct answers through multiple displaying menus. Text typing spans activities such as document editing and email writing; screen scrolling covers activities such as document reading and standard web browsing; drag & drop of images considers activities such as image processing and windows scrolling and movement; finally, menu browsing spans activities related to applications' menu selection and screen pointer precision.

Figure 2 depicts a high-level diagram of the experimental RVD testbed used in the subjective tests. Tests were performed in a dedicated lab for subjective studies, compliant with the recommendations provided by the QoE subjective studies standards [1]–[3]. Two testing stations were used in parallel to optimize the duration of the overall study and to evaluate more participants. All the components of the testbed are managed by a tele-commander system controlled by the tests' operator, which provides full control, automation, tracking, and most important, repeatability of the tests. To avoid any kind of disturbances on the participants' traffic, the connections between the tele-commander and the testbed components are realized through an isolated management network.

The up-link and down-link traffic between the RVD server and the thin-clients was routed through a modified version of the very well known NetEm network emulator [12] so as to control the different network performance levels under evaluation. Given that every generic RVD system runs on top of TCP as transport protocol, and based on the findings of previous work stating that network delay is the most impacting network feature on RD performance, we performed all the subjective tests by only modifying the network RTT. Setting the RTT of the end-to-end connection permits to control the responsiveness of the overall RVD system, impacting as such the experience of the end-users. Network RTT was varied between 50 ms and 500 ms, covering as such various of the different usage scenarios of RVD through multiple network access technologies (DSL, LTE, 3G/2G, etc.). The large RTT values particularly address broadband mobile scenarios, in which network delay is much more variable, and radio and cell-overloading issues result in very large latencies. We

Task	$\overline{Th_{up}}$	$\overline{Th_{down}}$	$\max(Th_{up})$	$\max(Th_{down})$
Typing	6.1 kbps	19.6 kbps	66.8 kbps	1.0 Mbps
Scrolling	5.1 kbps	62.3 kbps	68.1 kbps	1.3 Mbps
Drag & Drop	54.3 kbps	686.5 kbps	132.6 kbps	2.4 Mbps
Menu	42.5 kbps	459.4 kbps	121.9 kbps	2.8 Mbps

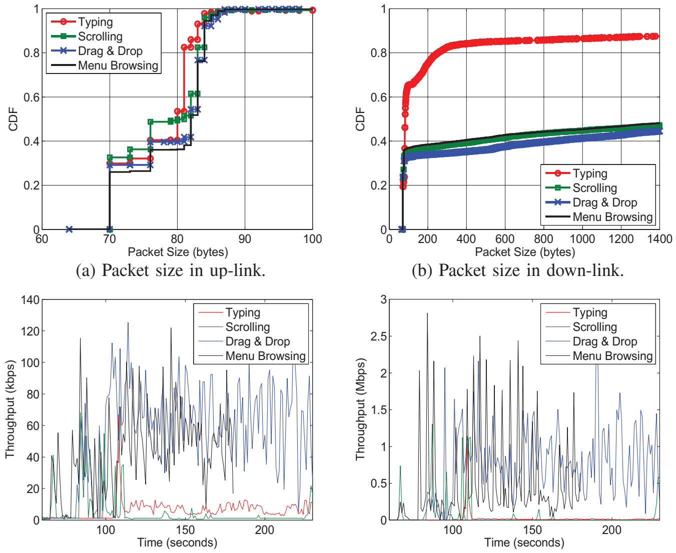
TABLE I. AVERAGE AND MAXIMUM THROUGHPUT ACHIEVED BY THE EVALUATED TASKS IN BOTH UP-LINK AND DOWN-LINK DIRECTIONS.

additionally tested a local desktop condition, in which users performed the same tasks in exactly the same desktop, but running locally on the laptop. This additional test case permits to verify how distant is the QoE of a RVD system from a standard local desktop. All the traffic packets were captured and exported to standard `pcap` traces for off-line analysis and traffic characterization using high-performance Endance DAG cards. Participants were compensated with vouchers for their participation in the tests, which proved to be sufficient for achieving correct involvement in the tasks.

Regarding application layer measurements, for every tested condition we tracked the time needed by the participant to completely achieve the corresponding task. In addition, we followed a similar approach to that developed in [6] to measure the response times of the RVD system for the different tasks and network conditions that were tested. These measurements were performed in a posterior phase to the subjective tests, using the well-known `AutoHotkey` application. Using AutoHotkey scripts, we were able to measure the time spent between the input of a key-stroke or a mouse click/movement and the corresponding screen update. Such an approach permits to develop technical mappings between QoE and response times, which represents the main performance feature perceived by the end-user [13], [14], independently of the underlying network conditions. Using these mappings, we additionally evaluated the relations between network bandwidth and QoE.

Concerning end-users feedback, participants were instructed to rate the *quality of the connection* and the *overall experience* with the application according to an ordinal ACR-9 Mean Opinion Score (MOS) scale [1], ranging from "bad" to "excellent". In this paper we shall only present those results regarding the overall experience of the user (MOS from now own), which better captures the essence of QoE. Participants also provided feedback on the *acceptability* of the application, stating whether they would continue using the application under the corresponding conditions or not. In addition, participants rated the level of difficulty they encountered in achieving the corresponding task, which permitted to draw some conclusions on the impacts of network performance on the RVD users' behavior. The MOS ratings and quality feedbacks were issued by participants through a custom questionnaire application running on the virtual desktops, which was issued immediately after a condition was tested.

Finally, a brief summary on participants' demographics: 23 participants were female and 29 male, the average age was 32 years old, with 28 participants being less than 30 years old. Around a quarter of the participants were students and almost 46% were employees. A big share of the participants (more than 56%) had a daily Internet usage between 1 and 5 hours, and around 14% were intensive Internet users, with more than 7 hours of daily usage.



(a) Packet size in up-link. (b) Packet size in down-link.

(c) Achieved up-link throughput. (d) Achieved down-link throughput.

Fig. 3. Characterization of the traffic generated by Citrix RVD systems.

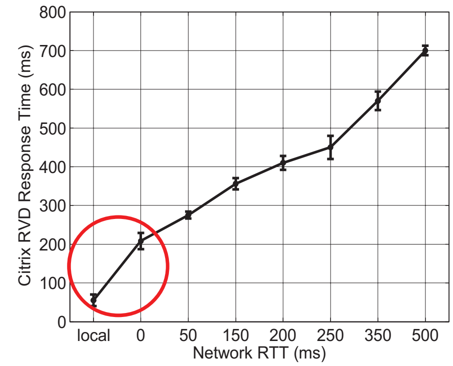


Fig. 4. Citrix response time. Even in optimal network delay conditions, Citrix RVD introduces an additional latency of about 150 ms w.r.t. a local desktop.

IV. RVD QoE and Network Performance

In this section we present and discuss the results of the subjective tests and the corresponding analysis. Firstly, we perform a brief characterization of the traffic generated by the different tasks in terms of packet sizes and throughput, which permits to gain more understating on the network requirements for such tasks. In the same direction we evaluate the delays introduced by Citrix, comparing the response time of the RVD system with the one achieved on a local desktop. Then we present the QoE analysis for RVD, particularly considering the correlations between QoE and network RTT in terms of user experience and acceptability. In addition, we perform a brief and approximated study on the impacts of down-link network bandwidth on RVD QoE, using the aforementioned mappings between response time and MOS ratings. Finally, we present some results on the difficulty and the time employed by the participants to achieve some of the evaluated tasks, which show the impacts of network performance on usage behavior.

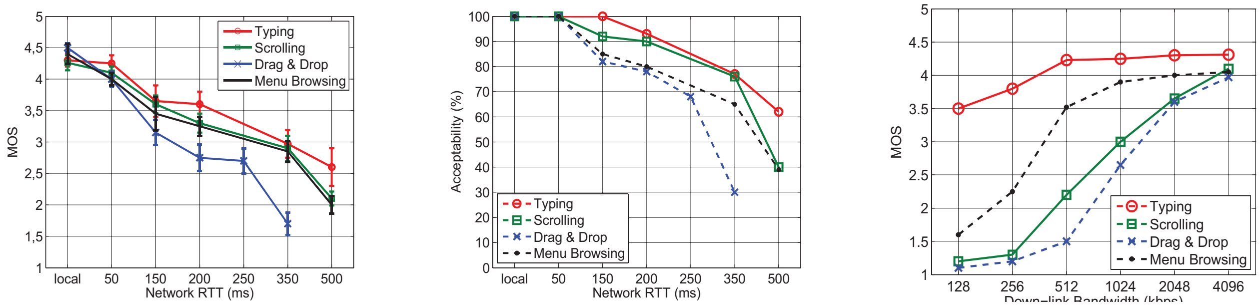
A. Traffic Characterization and Citrix Performance

The four evaluated tasks present different traffic patterns due to their different requirements in terms of interactivity. Figure 3 depicts a characterization of the packet size and the achieved throughput in both up-link and down-link directions. Regarding packet sizes in figures 3(a) and 3(b), the four tasks produce an almost identical pattern in the up-link direction, which is coherent with the fact that only user inputs are sent from the thin-client to the server. The up-link traffic is mainly composed of ACK packets to the down-link data and PSH packets, which allow to send user inputs with low processing delay at the server. The situation is very different in the down-link direction, where the actual screen updates are streamed on top of TCP towards the thin-client. Typing sends much less data than the other three tasks, which share a common packet size behavior among them, basically due to the high screen update rate of the corresponding applications. The surprisingly big packet sizes present in the CDF of the typing task correspond to the full screen updates incurred while opening the text editor application. Regarding throughput in figures 3(c) and 3(d), the different variations in both up-link and down-link directions are directly tied to the different interaction requirements of the underlying applications. For example, it is clear that moving images in the remote desktop screen causes a lot of screen updates sent in the down-link direction, which at the same time causes an increase in the up-link ACKs. Table I details the average and maximum throughput values achieved in both directions for all the tasks. While the requirements in terms of up-link bandwidth are minimal, large throughput peaks are observed in the down-link direction. As before, the high values for typing in the down-link direction correspond to the aforementioned full screen update. These results will be very useful to understand the influence of the down-link bandwidth on QoE, analyzed in section IV-C.

Figure 4 depicts the measured response times of the Citrix RVD system incurred in full screen updates (e.g., changing the background color of the complete desktop), while modifying the underlying network RTT. For the sake of comparison, the response time of the same full screen updates are measured in a local desktop. The additional latency of the Citrix RVD system is astonishing; even under perfect network conditions (i.e., RTT = 0 ms), it introduces an additional latency of about 150 ms w.r.t. a local desktop. This additional latency strongly impacts the QoE offered by Citrix systems in WAN scenarios, as we show in the following section.

B. Testing RTT Limits

We shall now discuss the results of the subjective tests in terms of the overall quality and the acceptability as declared by the participants in the four tested tasks. The typing, scrolling, and menu browsing tasks are tested with RTT values of 50, 150, 200, 350, and 500 ms. This range of RTT values considers typical operational values observed in different access technologies, particularly considering mobile broadband scenarios. For example, RTT in operational LTE and HSPA networks are close to 50 ms [16], whereas 500 ms are common values observed on EDGE scenarios. As we show next, the drag & drop of images task is more sensitive to high RTT values, due to the associated higher interactivity requirements and the heavy screen update rate. For this reason, we limit the analysis of drag & drop to a maximum RTT value of 350 ms, and we add an additional testing condition at RTT = 250 ms.



(a) Overall Quality vs. RTT. (b) Acceptability vs. RTT. (c) Overall Quality vs. DBW.

Fig. 5. Depending on their specific characteristics, different tasks have different QoE sensitivity to network impairments. RTT should be kept below 150 ms to achieve good QoE with Citrix RVD systems in generic desktop applications. DBW should be high enough to avoid shaping the down-link traffic.

Figure 5(a) depicts the MOS values issued by the participants regarding their overall experience with the corresponding RVD task and network RTT condition. The first interesting observation comes from our previous comment: the QoE sensitivity of the drag & drop task to higher delays is markedly different from the other three tasks. In the case of drag & drop, already a RTT value of 150 ms degrades the user experience to the limit of fair quality (i.e., MOS = 3), and the perceived quality rapidly degrades after a RTT of 250 ms. The typing task is clearly the most robust one against network delays, as even with a RTT of 200 ms users declare good experience (i.e., MOS $>$ 3.5), and fair quality is achieved up to 350 ms. Surprisingly enough, the QoE behaviors of scrolling and menu browsing are very similar in terms of overall quality. It is interesting to note that the maximum MOS ratings declared by the participants are never 5 but somewhere between 4.2 and 4.6. This is a well known phenomenon in QoE studies called *rating scale saturation*, where users hardly employ the limit values of the scale for their ratings [15].

Figure 5(b) shows the acceptability rates as declared by the participants. About 80% of acceptance rate is achieved in all the tasks for up to 200 ms of network RTT. Note that in the case of typing, acceptance rate is above 60% even for very poor network conditions (i.e., RTT = 500 ms), which once again evidences the strong existing correlation between QoE sensitivity and interactivity requirements of the corresponding application and task. As we said before, the drag & drop task becomes rapidly unacceptable after RTT = 250 ms, and a similar trend is observed for scrolling and menu browsing after 350 ms.

C. Finding Bandwidth Thresholds

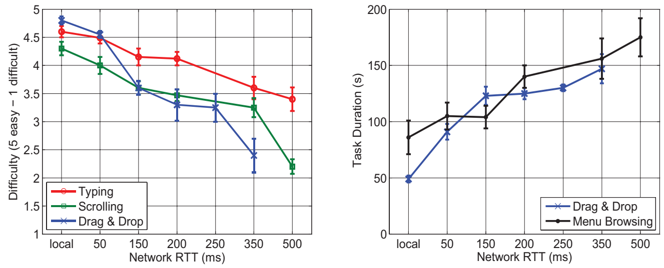
The independent network performance feature that is modified in the subjective tests performed in this study is network RTT. Given that the RVD system runs on top of TCP, both packets losses and bandwidth shortages will have a similar effect to that of RTT on the perceived performance of the overall system, resulting on an increase of the response time. However, specially when it comes to network bandwidth, it is interesting to find the QoE undergone by RVD users at different bandwidth thresholds. This can be achieved by relying on the mappings between RVD response times and QoE, which are directly available from the results of the subjective tests. We do not present these mappings in current paper, but we provide a brief description on how they are built.

The response time of the overall RVD system is the time elapsed between the input of a user and the corresponding screen update. By modifying the RTT in the subjective tests, participants experience different response times in each of the tested tasks. Therefore, for each RTT tested condition and for each evaluated task, the subjective tests provide a MOS value related to the specific response time. As previously explained in section III, the response times of the RVD system are measured in a posterior phase to the subjective tests. Combining the measured response times and the MOS ratings provided by the participants, we construct a mapping function for each of the evaluated tasks. With these mapping functions at hand we can evaluate the impact of other different network parameters on user experience, without the need of conducting new subjective tests. We simply set the corresponding network parameter (e.g., down-link bandwidth, packet losses, etc.), measure the response time in the same way as before, and map the result to a MOS value.

Figure 5(c) depicts the overall quality results obtained with the aid the aforementioned mapping functions, using the down-link bandwidth (DBW) as testing network parameter. Based on the characterization results presented in figure 3, we can claim that the requirements of up-link bandwidth are minimal in Citrx RVD systems, and therefore focus the analysis on the down-link direction. The range of DBW values goes up to 4 Mbps, which is high enough to avoid shaping the down-link traffic according to the results in table I. As expected, the typing task is the least sensitive to low DWB values, and good user experience is achieved even for very low speed connections (i.e., DBW = 128 kbps). The drag & drop and the scrolling tasks are the most sensitive to DBW provisioning, which comes from fact that both tasks may require a very interactive screen update rate, specially when doing fast scrolling and fast image movements (e.g., windows displacement). The most interesting observation is that all the tasks achieve good QoE when the down-link traffic is not shaped, which in the selected DBW range occurs for a DBW = 4 Mbps.

D. Analyzing User Behavior

To conclude with the analysis section, we present some selected results concerning users behavior and the productivity that a RVD user can achieve under changing network conditions. Figure 6(a) depicts the difficulty level encountered by



(a) Difficulty to perform the task. (b) Required time to complete the task.

Fig. 6. Impact of RTT on user behavior and productivity. A RVD user may take up to 3 times more to complete a task in poor network conditions.

the participants to perform the tested tasks, for different RTT values and for a local desktop scenario. Difficulty levels are measured on a 1 to 5 scale, being 1 very difficult and 5 easy. As expected, the higher the network RTT, the more difficulty the participants encountered in performing the different tasks as compared to a local desktop. Such an a-priori obvious result shows that user experience in RVD is not only about how smooth the application runs on the thin-client, but also about how difficult it could be for a user to interact with a system in which response times are high. This is additionally reflected in figure 6(b), where we plot the time required by the participants to complete the evaluation tasks. It is surprising to see how a RVD user may take up to 3 times more to complete a task in poor network conditions w.r.t. the time he requires to achieve the same task in a local desktop. This is of special interest in enterprise scenarios, where the productivity of a user working through a RVD system can be severely impacted by to high network delays.

V. Concluding Remarks

In this paper we have presented a complete study on the Quality of Experience in Remote Virtual Desktop services. By conducting extensive subjective tests on the experience undergone by 52 RVD users in a fully controlled Citrix-based RVD testbed, we have shown solid results on the interplays between network performance and the QoE declared by its users. We expect that such results will not only shed light on the challenging problem of QoE provisioning for general remote services like Cloud-based applications, but also provide guidelines for the future deployment of better RVD services.

The comparisons performed against the experience of users in local desktop scenarios show that Citrix RVD services in WAN scenarios are difficult to compare with locally running desktop applications, specially when large RTT and low downlink bandwidth values are experienced. However, good QoE levels can be expected when provisioning such RVD services over fast and low-delay connections, which could be even realized through current fast mobile access technologies such as HSPA+ and LTE. Our study has also shown evidence on how impacting to end-user productivity could be to provision RVD services through low performance connections, pushing forward the needs for QoE management techniques in current best-effort Internet.

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