The Effect of Latency on User Performance in Real-Time Strategy Games

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Abstract

Latency on the Internet is a well-known problem for interactive applications. The growth in interactive network games brings an increased importance in understanding the effects of latency on user performance. Classes of network games such as First Person Shooters (FPS) and Real-Time Strategy (RTS) differ in their user interaction model and hence susceptibility to latency. While previous work has measured the effects of latency on FPS games, there has been no systematic investigation of the effects of latency on RTS games. In this work, we design and conduct user studies that measure the impact of latency on user performance on three of the most popular RTS games. As a foundation for the research, we separated typical RTS user interactions into the basic components of explore, build and combat, and analyzed each individually. We find modest statistical correlations between user performance and latency for exploration, but very weak correlations for building and combat. Overall, the effect of even very high latency, while noticeable to users, has a negligible effect on the outcome of the game. We attribute this somewhat surprising result to the nature of RTS game-play that clearly favors strategy over the real-time aspects.

1 Introduction

Over the past decade, the Internet has grown in popularity and capability at exceptional rates. In 1997, there were 36.6 million homes with computers and only 18 million of them had Internet access [7]. By the year 2000, the number of homes with computers had grown to 51 million, 41.5 million of which had Internet access, and many with broadband Internet connections such as cable modems and DSL lines.

This growth in Internet popularity and capability has led to an increasingly diverse set of Internet applications with varying network behaviors and requirements. Characterizing the behavior of these applications involves studying the key metrics of latency and throughput. Traditional applications such as file transfer, Usenet news and email are primarily concerned with throughput and can tolerate delays on the order of minutes. Web browsers are also concerned with throughput, but the interactive nature of browsing requires latencies on the order of seconds or at most tens of seconds [5]. Emerging real-time applications such as IP telephony and networked games typically have the lowest throughput requirements but are even less tolerant of latency than other applications. Knowing how these real-time applications react to latency and loss is the crucial first step in designing the next generation network hardware and software that will support their requirements. In addition, classifications of real-time applications according to latency tolerance will enable designers, developers and engineers to make informed decisions on appropriate quality for classes under such architectures as DiffServ [6].

The most popular real-time applications are multi-player network computer games that can make up around half of the top 25 types of non-traditional traffic for some Internet links [14] and are predicted to make up over 25% of Local Area Network (LAN) traffic by the year 2010. In 2000, the U.S. economy only grew 7.4% while the computer and video game industry grew by 14.9%, outpacing growth in other high-tech industries and even Hollywood over the previous five years [11]. In 2002, over 221 million computer and video games were sold, or almost two games for every household in America.[1] Knowledge of how network related issues, such as latency and packet loss, affect the usability of games can be of great use to the companies that make these games, network software and equipment manufacturers, Internet Service Providers (ISPs), and the research community at large. In particular, if established latency requirements and any associated trade-offs were known, ISPs could establish tariffs based on customers' indicated maximum delays, requested Quality of Service (QoS) and the ISP's ability to meet these demands.

Two of the most popular categories of real-time network games are *First Person Shooter* (FPS) games and *Real-Time Strategy* (RTS) games. FPS games, first made popular by Doom,[2] have the player view the world through the eyes of a character (the first person). Players then move around slaying monsters and other players with an amalgamation of ranged weaponry (the shooter). RTS games, first made popular by Dune 2,[3] are generally characterized by resource collection, unit construction, and battles that consist of large numbers of soldiers going through a repetitive, animated attack.

While there has been research qualitatively characterizing the effects of latency for car racing [16], custom games [19] and popular FPS games [2, 10] as well as a general awareness of latency issues [3, 4, 12, 15], quantitative studies of the effects of latency on RTS games have been lacking. Moreover, it is unlikely that all games, such as FPS games, have the same network requirements as do RTS games. In many FPS games, exact positioning and timing is required, because, for example, a target must still be at the location where the player aimed in order for the shot to hit. In many RTS games, the positioning and timing is more forgiving because, for instance, a command can be issued to attack a unit, regardless of its current location or its direction and time of movement.

This work studies the effect of latency on user performance and network traffic for three of the most popular RTS games, all from well-established game lineages: Blizzard's Warcraft III®,[4] the latest and best selling [18] RTS game from the Warcraft lineage; Microsoft and Ensemble Studios' Age of Mythology®,[5] the latest extension of the extremely popular Age of Empires series [17]; and Electronic Arts' Command and Conquer: Generals®,[6] the latest installment in the long line of successful Command and Conquer games, first started by Westwood. We quantify the effect of latency on user performance in RTS games by analyzing the results of controlled research experiments designed to measure application-centric quality of service over a range of induced latencies. As a foundation for RTS research, we divide RTS games up into fundamental game components of building, exploration and combat. We then develop multiple criteria for measuring user performance in RTS games and use these criteria in very carefully designed experiments to determine user performance over a range of latency conditions. We focus initially on Warcraft III, providing in-depth analysis across application, network and user levels. We then apply the same methodology and analysis to Age of Mythology and Command and Conquer: Generals in order to generalize the Warcraft III results to other RTS games.

We find that latencies up to several seconds have little effect on the final outcomes of building, exploration, and most combat. Although, the effectiveness of certain strategies that involve precise timing of events are influenced by the amount of latency, very few such strategies prevail in typical RTS games. Overall, strategy plays a much larger role in determining the outcome of the game than does latency. We conclude that RTS games should be placed in a different QoS class than applications with stringent latency constraints, such as FPS games or audio-conferences, since RTS games have latency requirements more similar to those of Web browsing.

The rest of this paper is organized as follows:

[1] Top Ten Industry Facts, IDSA, http://www.idsa.com/-pressroom.html

[2] http://www.idsoftware.com/games/doom/

[3] http://www.dune2k.com/duniverse/dune2/

[4] http://www.blizzard.com/war3/

[5] http://www.microsoft.com/games/ageofmythology/

[6] http://www.eagames.com/official/cc_generals/

Section 2 presents background information on RTS games; Section 3 describes our approach to measure the effects of latency on RTS games; Section 4 analyzes the application, network and user results from our experiments with Warcraft III; Section 5 generalizes the results of Warcraft III by applying our methodology to Age of Mythology and Command and Conquer: Generals; Section 6 summarizes our conclusions; and Section 7 presents possible future work.

2 Background

In Real Time Strategy (RTS) games, players construct buildings and fighting units, and issue commands that cause the units to move, engage enemy units in battle, and build structures. Games are played on one of many possible maps, which are either provided with the game or custom built by players.

RTS games typically use a centralized server in a client-server architecture with at most 10s of participants, either over the Internet or on a LAN. Some RTS publishers provide hosted game services, such as Blizzard's Battle.net,[7] to facilitate Internet game play. For a LAN game, users can use one client's machine as a server, too, by choosing a scenario and then letting other clients join the game.

At the beginning of a game, players typically can choose among a number of "races" (Humans, Orcs, Undead and Night Elves in Warcraft III; Greeks, Egyptians and Norse in Age of Mythology; and the USA, China, and Global Liberation Army in Command and Conquer: Generals). Our research focuses on one race from each game (Humans, Greeks and USA, respectively), but since RTS game developers put great effort into making the races equivalent in overall power, our results should generalize to the other races. There are a number of ways in which players can be competitively grouped. In a free-for-all game, all players vie to have the last remaining army on the map. Players can also team up against each other and/or against artificially intelligent computer-controlled players in myriad ways.

[7]http://www.battle.net/

Figure 1: Warcraft III - Screenshot of Undead Army Attacking a Town.

As an example of RTS gameplay, Figure 1 shows a Warcraft III screenshot of a Human town under attack from an Undead army. The Undead are in the upper left area of the screen and Human workers can be seen carrying lumber to the Town Hall and doing other activities. The bottom left of the screen shows a mini-map, illustrating unexplored areas of the larger world.

Structure control and unit control are two major aspects of RTS games. Structure control consists of selecting what building structures are to be built or upgraded, what units are to be produced and what technologies are to be developed. In order to accomplish these tasks, worker units must be sent to gather resources such as money and materials. Others must select structures to produce, where some structures produce standard army units (such as Archers, Toxotes, or Bazookamen), while other structures produce advanced army units (such as Sorceresses, Minotaurs or Tanks), and other structures provide defensive cover fire in the case of an enemy attack. Effective structure control requires strategy in knowing when and where to build, upgrade, and research.

Unit control can be broken up into three subcategories: building, exploration and combat. Building overlaps with structure control as it is the management of workers in harvesting resources and building and repairing buildings. Exploration allows players to determine geography and find enemy towns or units. Combat allows units to kill other units, to defend towns, and secure territory. There are various battle strategies that can be deployed, from simple strategies such as deploying ranged attackers in the rear of the army to advanced strategies involving pitting individual units against opposing units they counter the best. At a minimum the player can let the computer's artificial intelligence handle the units.

3 Approach

In order to empirically measure the effects of latency on RTS games, we first developed a experimental methodology for Warcraft III, described in this section, and then apply this methodology to Age of Mythology and Command and Conquer: Generals, described in Section 5. Our methodology:

- Categorize user interactions in typical RTS games and construct campaign maps that exercise each category (see Section 3.1).
- Determine criteria to quantitatively measure RTS game performance (see Section 3.2).
- Construct an environment for measuring the effects of latency on RTS games (see Section 3.3).
- Conduct pilot studies (see Section 3.4) and then numerous user studies for each RTS category over a range of latencies, recording the performance measurements.
- Analyze the results (see Section 4).

3.1 Categories of RTS Interaction

Through pilot studies and hours of play testing, we determined there are three main user interaction components of an RTS game: *building* when players gather resources, construct defenses and recruit units; *exploration* when players send units out to determine geographic layout and location of other players' units; and *combat* when players engage their units with other units in battle. Since all components require user interaction, we

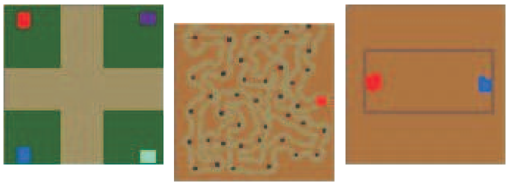

Figure 2: RTS Component Maps: Build (left), Explore (middle), Combat (right).

hypothesized that under each component, user performance would degrade as latency increased. We built multi-player maps that isolated each component so that we could use experiments to measure the effects of latency on that component.

For the Warcraft III building map[8] (Figure 2 (left)), we divided the map into four quarters using mountain ranges that units could not cross. Each player started with a Town Hall and four Peasants, had unlimited gold and lumber available, and had to research, build, and upgrade the complete Human technology tree as fast as possible. We added triggers to the map that disabled players' ability to build more than one building in order to provide consistency and reduce confusion, as well as a trigger to display the total time since the beginning of the game.

For the Warcraft III exploration map (Figure 2 (middle)), we designed a raised path that kept units on a general exploration course. The player had to guide a unit along the winding path and step on numerous way-points. Map triggers kept track of the player's time to complete the map.

For the Warcraft III combat map (Figure 2 (right)), we designed a small player versus player arena in which each player controlled a small army consisting of a level 6 Hero (a Mountain King), two Knights, four Footmen, two Riflemen, a Sorceress, and two Priests.

3.2 RTS Performance Criteria

We sought to devise general methods of game performance that could be applied to any RTS game. For both the building and exploration maps we recorded the game length as a measure of perfor-

[8]The Warcraft III maps can be downloaded at http://-perform.wpi.edu/downloads/#war3

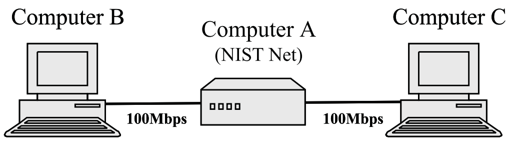

Figure 3: Experimental Testbed Setup.

mance. For the combat maps, in addition to the game length, we recorded each player's unit score and which player won. At a minimum, the number of units a player starts with plus the number of units killed determines the unit score. Some RTS games, such as Warcraft III and Age of Mythology, also include a point value for individual units, with more powerful units being worth more points. The breakdown of points for the individual Human units used in our Warcraft III combat map are listed in Table 1.

Unit	Points
Footman	160
Priest	170
Sorceress	200
Rifleman	270
Knight	350
Level 6 Hero	600

Table 1: Warcraft III - Unit Point Values

3.3 Experimental Setup

Figure 3 depicts our experimental testbed setup, which consisted of PCs connected on a private network subnet. Computer A was a dual-processor Pentium-2 300 MHz running Mandrake Linux that routed packets with 100 Mbps connections to the computers B and C. Computer B was a Pentium-2 350 MHz with 256 MB of RAM, and a 64 MB Geforce2 Ti graphics card running Windows 98. Computer C was a Pentium-4 1.3 GHz with 256 MB of memory and a 64 MB Geforce2 graphics card running Windows XP.

The recommended specifications for Warcraft III are a 400 MHz Pentium-2 or equivalent, 128 MB of RAM, and an 8 MB 3D video card (TNT, i810, Voodoo 3, Rage 128 equivalent or better) with DirectX® 8.1 support. Although computer B was only 350 MHz, the graphics cards and extra memory that it contained made up for this slight deficiency, and all computers were capable of rendering 30 frames per second[9] even during combat. We used Warcraft III version 1.04 for all user tests and version 1.05 for the network traces due to the Battle.net requirements.

We installed NIST Net[10] on computer A. NIST Net allows emulation of a wide variety of network conditions by giving control at the IP level, including fine tuning of latency and variation in latency (jitter). We used NIST Net to induce latency (and jitter) for one of the machines in a game, while the other, acting as the server, played with no induced latency. Also, in order to analyze the network footprints of our RTS games, we ran Ethereal[11] to capture packet traces for network analysis.

3.4 Pilot Studies

First, we conducted Warcraft III pilot studies to help determine the range of viable latencies on which to focus. Our first pilot studies consisted of two-player games in which one player was subjected an increasing amount of latency and the other player experienced none. Initially, each player had a Town Hall and a gold mine placed a fixed distance away from the Town Hall; and second, each player had two identical units that did one point of damage per hit. We setup triggers in the maps so games could be run automatically and ran repeated tests with one player (the lagged player) having increasingly greater latency. We found both players did equally well, gaining gold and inflicting damage at exactly the same rate. In addition, both players saw exactly the same events on each screen, except the player with added latency saw events later than the player without added latency.

From these pilot studies, we made two important observations about latency compensation in Warcraft III:

First, the game does not use handicapping in the game to equalize latencies across all players. Both lagged and non-lagged players see events happen at the real-time rate, regardless of the latency of the other player. The lagged player has events ex-

[9]Tested with *fraps*, http://www.fraps.com/
[10]http://snad.ncsl.nist.gov/itg/nistnet/
[11]http://www.ethereal.com/

ecuted later by an amount equal to the induced latency.

Second, the game does not have inconsistent game states, which implies no dead reckoning [9] or client-side predictions [3]. The actions that occur on each machine are identical; there is no prediction of user actions and then correction upon some later time if the predictions are inconsistent with the actual game state.

Thus, clients must communicate any user actions to the server before executing them. After that, the commands themselves are executed identically on all machines in the game.

For the real experimental runs, the maps were not automated and we pitted one player against another player. The first player was the server with no induced latency. The second player was the client that was subjected to induced latencies ranging from 0 to 3500 ms. Since this range is even broader than typically found in dialup modems [13], we concentrated our data points on ranges of more typical latencies [1] which are less than 1000 ms.

From traces collected during our pilot studies, we determined that clients communicate only with the server but not directly with other clients. Servers combine data from multiple clients before distributing data. Each machine maintains a complete copy of the game state, and to an extent, all outcomes are predetermined upon initiation of the action. Command data is only transferred upon the issuance of a command, and never again during the life of the event. For instance, the commands to initiate a large-scale battle are propagated to all clients once, resulting in an increase in the packet payload size, but the battle itself has no effect on traffic unless further commands are issued as the battle is carried out.

4 Warcraft III Analysis

We analyzed our experimental data at three levels: Section 4.1 contains our analysis of the application level data we collected from our Warcraft III user studies; Section 4.2 analyzes network level traffic for a Warcraft III LAN game and two Warcraft III Battle.net Internet games as well as network level traffic for combat games with three levels of induced latency; and Section 4.3 summarizes the user level observation data we collected during the Warcraft III user studies.

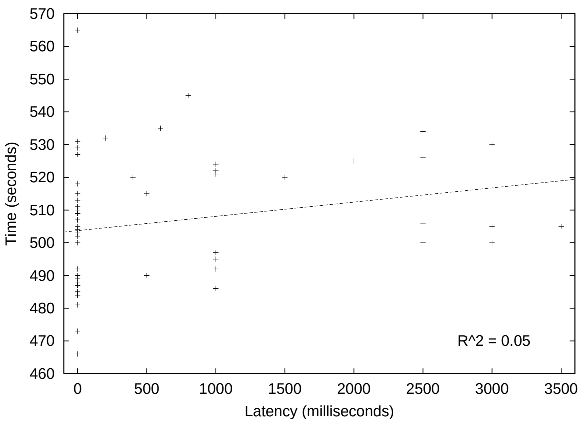

Figure 4: Warcraft III - Build Time versus Latency.

4.1 Application Level Analysis

This section analyzes the results from each of our test maps, starting with building (Section 4.1.1), then exploration (Section 4.1.2) and lastly combat (Section 4.1.3).

4.1.1 Building

Figure 4 illustrates the effect of latency on the total time required to construct every building and research every upgrade (the technology tree) for the Human race from our test map. The graph shows the build time versus latency for all runs, as well as a best-fit line for the data. Under conditions with no induced latency, building the technology tree takes about 8 minutes. Latency values of up to 3.5 seconds increase total build time by at most 14 seconds, which is less than 1% of the total time for this short game. The coefficient of determination[12] is 0.05, indicating there is very little statistical correlation between latency and building. In addition, the statistical correlation observed in a real game environment is likely to be even lower. A

[12] The coefficient of determination (R^2) represents the fraction of variability in y that can be explained by the variability in x. In the linear regression case, R^2 is simply the square of the correlation coefficient. An R^2 of 1 represents perfect correlation while an R^2 of 0 represents no correlation.

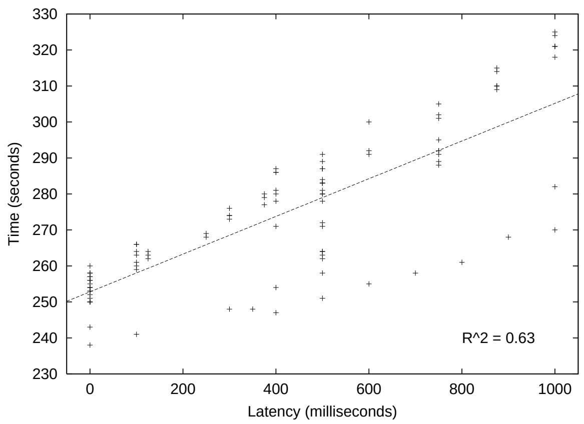

Figure 5: Warcraft III - Explore Time versus Latency.

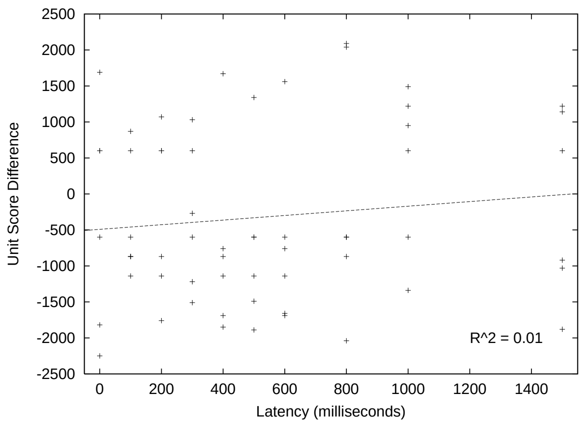

Figure 6: Warcraft III - Unit Score Difference versus Latency.

real game would have a longer game time and produce different numbers of buildings (such as more than one farm) and players would build their towns in strategic layouts instead of in random pattern. Finally, time is often spent in a real game attending to other matters so that the speed of building the base is not of utmost importance. Our conclusion is that any effect latency may have on building would have no significant impact on the outcome of typical Warcraft III games.

4.1.2 Exploration

Figure 5 illustrates the effect of latency on the exploration of our test map. The graph shows the exploration time versus latency for all runs, as well as a best-fit line for the data. The overall correlation between explore time and latency is modest (0.63), but can be high (0.95) for individual users. The first 8-10 games of a test typically showed a downward vertical component where exploration times decreased. We attribute this to the player learning the map, gaining from the knowledge in subsequent games. Once the map is known, all data shows a linear relationships between latency and time to explore. Overall, while there is a statistical correlation for explore time versus latency, the effect of an additional 6 seconds of exploration time for every 100 ms of latency would be insignificant in a real game. In addition, it is likely that high latency players in a real game may try to adapt to the latency in various ways during exploration. For instance, high latency players may discover that they achieve better results by spending less time actively controlling their units during exploration and thus decide to send them for long distances with each move command instead of micro-managing them for shorter distances.

4.1.3 Combat

Figure 6 shows the unit score difference versus latency for all runs, as well as a best-fit line for the data. The unit score difference is the non-lagged player's unit score minus the lagged player's unit score. For our Warcraft III combat map, the maximum difference (if one player loses all units and the other loses none) is +/-3020. From Figure 6, there is a slight upward trend in that the score difference increases as latency increases, but the coefficient of determination is an extremely low 0.01. Moreover, the difference in points from no induced latency to one second of induced latency is only about one unit, an insignificant amount in the large battles that are typical in Warcraft III. Thus, we conclude that latency has little effect on the individual units in combat.

Figure 7 illustrates the effect of latency on combat outcome from our test map. The graph shows the percentage of games won by the non-lagged host versus the latency of the lagged client. Even though there is a slight upward trend in the data, the coefficient of determination is an extremely low 0.07, indicating there is little statistical signif-

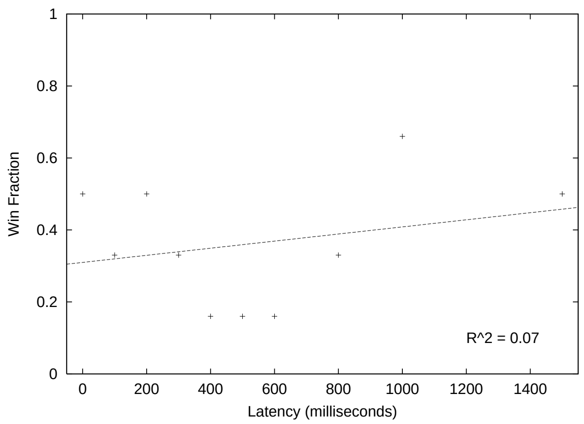

Figure 7: Warcraft III - Combat Games Won by Host (non-lagged) versus Latency (on the Client).

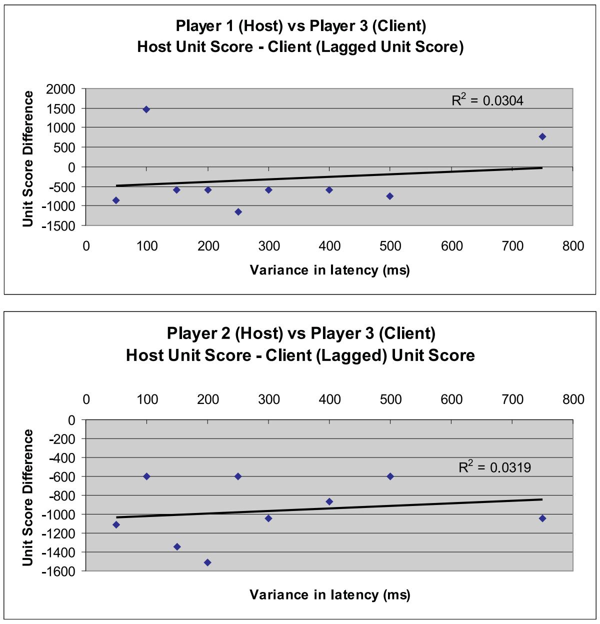

Figure 8: Warcraft III - Unit Score Difference versus Variable Latency: Player 1 versus Player 3 (top), Player 2 versus Player 3 (bottom).

icance. Thus, we conclude that latency has little effect on the overall outcome of combat.

While the previous studies measured the effects of fixed latency on user performance, we also examined the effects of variable latency. For these tests, we set NIST Net to induce an average latency of zero[13] and varied the standard deviation.

Figure 8 shows games for 2 pairs of users with a standard deviation of latencies from a normal distribution with mean zero. Figure 8 (top) shows player 1 winning two games, one at 100 ms, and then again at 750 ms, while losing the games in between, all by similar margins of 1 or 2 units. Figure 8 (bottom) shows Player 3 consistently beating his opponent in every game, but by varying margins. Neither graph shows a significant statistical relationship between the variable latency and success in combat, similar to the results with constant latency.

Overall, both from a direct conclusion from our data and with extrapolation into a full game, we find that the effect of latency on the outcome of a Warcraft III game is negligible over a range of practical latencies.

4.2 Network Level Analysis

Among other things, a better understanding of network game traffic can help design networks and architectures that more effectively accommodate network game traffic footprints. Furthermore, careful empirical measurements of network games can provide the data required for accurate simulations, a typical tool for evaluating network research.

4.2.1 Traffic for Full Games

For most Warcraft III Internet games, the server is via Battle.net,[14] a free service that allows Blizzard's Starcraft, Diablo and Warcraft players to initiate multi-player games over the Internet. We packet traced three full (20-30 minute) games, two played over Battle.net and one played over a LAN.[15] The LAN game was 1 player versus 1 player (1v1), and the Battle.net games had 1 player versus 1 player game and a 2 player team versus another 2 player team (2v2) game. Unlike other popular networked games [8] (and unlike Age of Mythology and Command and Conquer: Generals), Warcraft III uses TCP as the transport protocol with port 6112 for the server. All IP traces were performed

[13]Our testbed had about 1 ms of base latency from client to server.

[14]http://www.battle.net/

[15]The Warcraft III network traces can be downloaded at http://perform.wpi.edu/downloads/#war3

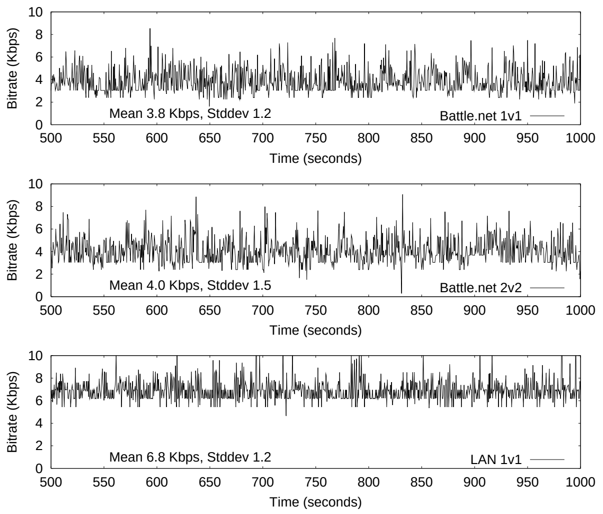

Figure 9: Warcraft III - Bitrate versus Time.

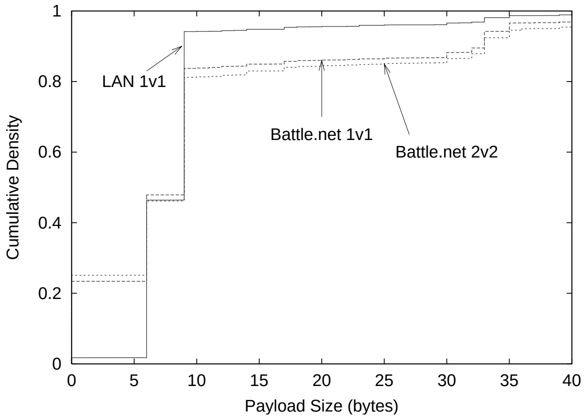

Figure 10: Warcraft III - Payload Distributions.

on the client machines. For reference, the round-trip time averages for the Battle.net games were about 100 ms and each game had less than 0.1% data loss.

Figure 9 depicts the bitrate (including IP headers) taken in 500 ms intervals for the three packet traces. Only the intervals 500-1000 seconds are shown to illustrate more detail, but the bitrate pattern throughout each game is similar to the interval shown. Overall, the variance in network bitrate for all three traces is similar, with the average bitrate for the LAN being slightly higher (6.8 Kbps) than the Battle.net traces (3.8 Kbps and 4.0 Kbps). All three traces have very low bitrates that can easily be achieved with a modem. In comparison, Starcraft,[16] the previous generation RTS game from Blizzard, has a bitrate of about 5 Kbps for a 2 player game [8], similar to that of Warcraft III.

Figure 10 depicts the cumulative density functions (CDFs) of the payload sizes for all packet traces (incoming and outgoing). The median payload sizes are all very small, only 9 bytes. The two most common payload sizes are 6 and 9 bytes. Less than 1% of the payloads for any game are over 40 bytes with the Battle.net games having slightly more larger packets. The 2v2 player Battle.net game has a distribution with slightly larger payloads, most likely because of command aggregation across users at the Battle.net server. For comparison, Starcraft has typical packet sizes of 122 and 132 bytes [8], while Warcraft III packets are most commonly 46 or 49 bytes in size (including headers).

Overall, Warcraft III sends considerably smaller packets than the typical Internet traffic packet size of over 400 bytes [14]. The number of players does not have a significant effect on the packet sizes, either. Warcraft III packet sizes are consistent throughout the game and are not significantly influenced by the action in the game. Since current Internet routers are designed for large transfers with large packets, there may be opportunities to improve network architectures to better manage and support game traffic.

Warcraft III sends out packets at regular intervals. Table 2 shows the inter-packet times that we observed for incoming and outgoing packets during the games we traced. In our local area network game, Warcraft maintained a very steady inter-packet rate of approximately one packet every 1/10th of a second both incoming and outgoing. With our Battle.net games, the timing interval was lower, down to one packet every 200 ms incoming and one packet every 160 ms outgoing.

Figure 11 depicts the CDFs for inter-packet times (incoming and outgoing). The LAN game has a much more consistent packet rate while the Battle.net Internet game varies considerably more. The median times for the Battle.net games are around 225 ms compared with around 100 ms for

[16]http://www.blizzard.com/worlds-starcraft.shtml

	1v1 LAN	1v1 B.net	2v2 B.net
In Mean	104	201	201
In Std Dev	18.6	79.1	78.1
Out Mean	104	165	159
Out Std Dev	19.4	87.4	88.2

Table 2: Warcraft III - Inter-packet Summary Statistics (ms).

	Packet Count		Bitrate (Kbps)	
Latency	Mean	Std Dev	Mean	Std Dev
0 ms	1886	230	7.2	0.6
500 ms	550	292	2.3	0.6
1000 ms	255	123	2.1	0.5

Table 3: Warcraft III - Packets and Bitrate.

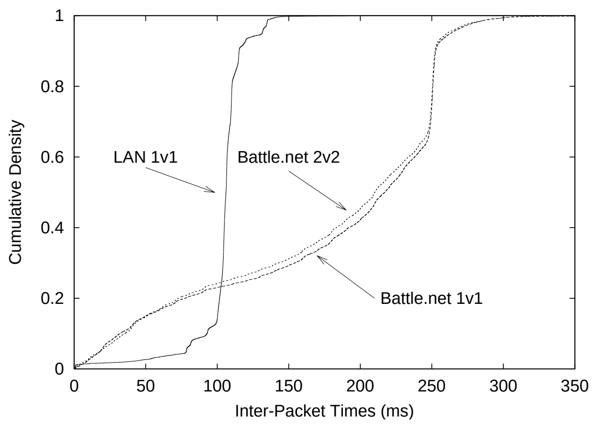

Figure 11: Warcraft III - Inter-packet Distributions.

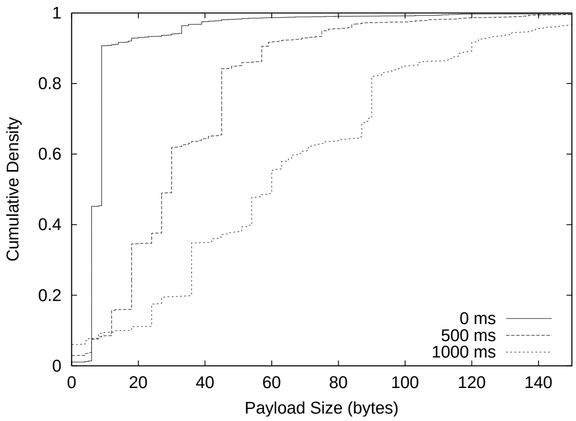

Figure 12: Warcraft III - Combat Payload Distributions.

the LAN game. The 1v1 player Battle.net game exhibits about the same inter-packet times as does the 2v2 player Battle.net game.

4.2.2 Combat Traffic and Latency

From Section 4.2.1, the differences between the Battle.net game traces which had latencies around 100 ms and the LAN game traces which had latencies around 1 ms suggest Warcraft III network traffic patterns change at least slightly with changes in latency. In this section, we analyze traces over a range of latencies in an attempt to quantitatively determine how Warcraft III network traffic differs with different latencies.

We packet traced games with our combat map at latencies of 0 ms, 500 ms, and 1000 ms with three games at each latency. All games took similar amounts of time (around 2 minutes each). The first phase (about 30 seconds long) of the combat games mostly involved the two armies moving towards each other, so there were few user commands and little network traffic. Thus, we removed the first 30 seconds of data from each trace for all subsequent analysis.

Table 3 shows the mean number of packets sent and the standard deviation across the three runs for each latency. Also shown is the mean bitrate (including IP headers) over 500 ms intervals as well as the standard deviation. The number of packets (incoming and outgoing) decreases as the latency increases, with the combat games with 500 ms and 1000 ms of latency sending only about 1/3rd and 1/8th as many packets, respectively, as the game with no added latency.

The 0 ms latency combat game produces about the same bitrate as does the full LAN game, shown in Figure 9. The 500 ms latency and the 1000 ms latency combat games have about 1/4th the bitrate as the 0 ms latency game and both the 500 ms latency and the 1000 ms latency games produce less bitrate than do the Battle.net games. This data suggests that the Warcraft III bitrate decreases with an increase in latency up to 500 ms, but remains constant for latencies beyond 500 ms.

Figure 12 depicts the CDFs of the payload

Latency	Commands Payload
0 ms	45.2 Kbytes
500 ms	46.3 Kbytes
1000 ms	45.0 Kbytes

Table 4: Warcraft III - Sum of Command Payloads.

sizes for all packet traces (incoming and outgoing), grouped into the three latencies. The median payload sizes increase from 9 bytes at 0 ms, to 30 bytes at 500 ms and to 60 bytes at 1000 ms. Less than 10% of the packets for any game are empty acknowledgments (payload size of 0). Overall, the distributions vary considerably with latency with higher latencies having larger packets. This suggests that at higher latencies, there is command aggregation at either the TCP or application level, meaning more Warcraft III commands are placed into each IP packet.

Based on Warcraft III traffic analysis during our pilot studies, we assume that there is an application overhead of 6 bytes for each packet issued, possibly used by Warcraft to indicate command sequence numbers or timing information. If we remove this overhead from the traces by subtracting 6 bytes from each packet, we can assume the "leftover" payloads are the result of user commands. Table 4 shows the sum of the command payloads over all the traces for each latency. The sum of the command payloads is very similar for each latency, which suggests that the commands issued by users are very similar, regardless of the network latency.

4.3 User Level Analysis

While we did not provide a way to quantify player perceptions, we did note player comments and observed trends during and after our user studies.

Players observed that it was relatively easy to adjust their strategy to compensate for latencies between 0 ms and 500 ms. The game still appeared to run smoothly, and although the delays in executing commands were perceptible as latencies approached 500 ms, it was relatively easy to estimate this delay and react accordingly. For latencies above 800 ms, the game appeared erratic which made for a degraded game experience. Without a short response time when executing commands, gamers thought it was difficult to implement particular strategies.

The exact point at which a player perceived a degraded game experience was between 500 ms and 800 ms but varied from person to person based on strategy and skill level. A strategy that relied heavily on micro-management of units was more sensitive to latency than a strategy that was less focused on individual unit control. What game aspects that a player chooses to micro-manage also had an effect on how perceived latency affected the gaming experience. A player that micro-managed the building rather than combat was much less likely to be aggravated by latency than a player that micro-managed combat units. Also, a mistake during combat that appeared to be the result of high latency was viewed, rightly or wrongly, as more serious than a mistake during building.

Thus, while latency does not necessarily affect the outcome of a Warcraft III game, if high enough, perceived latency does affect a user's gaming experience.

5 Other Real-Time Strategy Games

In order to generalize the findings from Section 4, we applied the methodology developed in Section 3 to two additional RTS games, both the latest extensions in a line of popular games: The Age of Mythology (AoM) and Command and Conquer: Generals (CCG).

For AoM, we used version 1.06 which had system requirements of a 450 MHz processor, 128 MB RAM, and 16 MB 3D video card, all met by our testbed. The building and exploration maps for AoM[17] and CCG were similar to those used for Warcraft III, described in Section 3.1. As in our Warcraft III tests, the AoM combat maps had two equal armies, where each army had eight Hoplites, ten Peltasts, five Popodromos, four Minotaurs, and two Heroes (Heracles and Bellerophon). The points for each unit is related to the resources they cost to create and the amount of favor (a special resource) they require. The breakdown of points for the units

[17]The Age of Mythology maps can be downloaded at http://perform.wpi.edu/downloads/#aom

used in our AoM combat map are listed in Table 5.

Unit	Points
Peltasts	8
Hoplites	9
Popodromos	11
Heracles	41
Minotaurs	43
Bellerophon	49

Table 5: Age of Mythology - Unit Point Values

For CCG, we used version 1.6 which had system requirements of an 800 MHz processor, 128 MB RAM, and a 32 MB AGP video card. For the CCG tests, we replaced computer B (see Figure 3) with a Pentium-3 800 MHz with 256 MB of RAM and a 64 MB Geforce2 Ti graphics card in order to meet these specifications. For the CCG combat maps, each army had three Crusader Tanks, two Humvees, ten Riflemen, and eight Bazookamen. There was no readily available scores for the CCG units, so we assume each unit is worth one point.

As for Warcraft III, we present the same three levels of analysis: Section 5.1 contains our analysis of the application level data we collected from our AoM and CCG user studies; Section 5.2 analyzes network level traffic for full AoM and CCG games with three levels of induced latency; and Section 5.3 summarizes the observation data we collected during the AoM and CCG user studies.

5.1 Application Level Analysis

This section analyzes the results from each of our test maps for AoM and CCG, starting with building (Section 4.1.1), then exploration (Section 4.1.2) and lastly combat (Section 4.1.3).

5.1.1 Building

Figure 13 and Figure 14 illustrate the effect of latency on the total time required to construct the technology trees for the Greeks and USA faction from our test maps. The graphs show the build time versus latency for all runs, as well as a best-fit line for the data. The coefficients of determination (0.14 and 0.21) are both very low indicating there is very little statistical correlation between

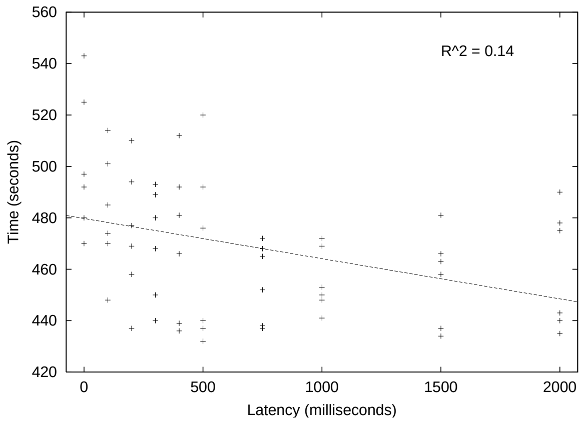

Figure 13: Age of Mythology - Build Time versus Latency.

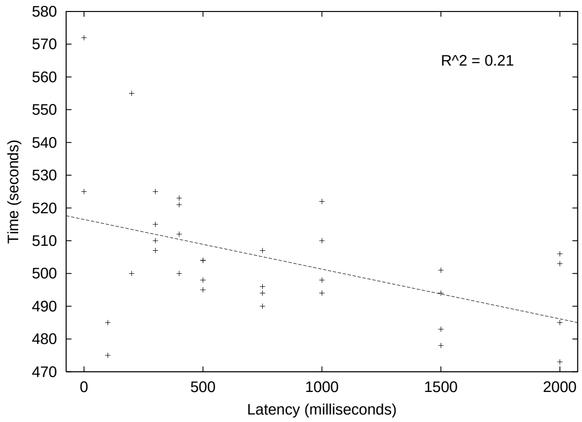

Figure 14: Command and Conquer: Generals - Build Time versus Latency.

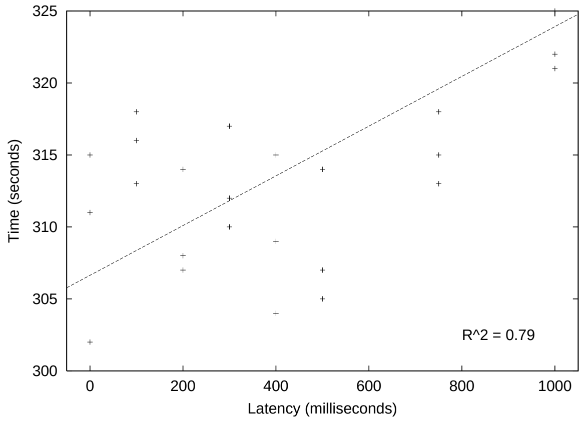

Figure 15: Age of Mythology - Explore Time versus Latency.

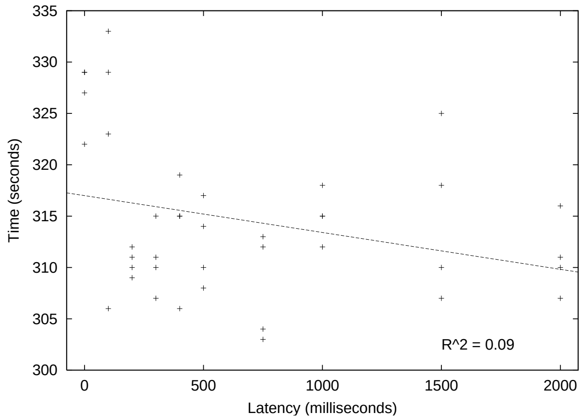

Figure 16: Command and Conquer: Generals - Explore Time versus Latency.

latency and building. In fact, the trend lines suggests an inverse correlation between latency and building, thus further discounting any relevant statistical correlation. Combined with the data on building in Warcraft III (Section 4.1.1), our conclusion is that latencies have no significant impact on building in typical RTS games.

5.1.2 Exploration

Figure 15 and Figure 16 illustrate the effect of latency on the exploration of our test maps. The graphs show the exploration time versus latency for all runs, as well as a best-fit line for the data. The overall correlation between explore time and

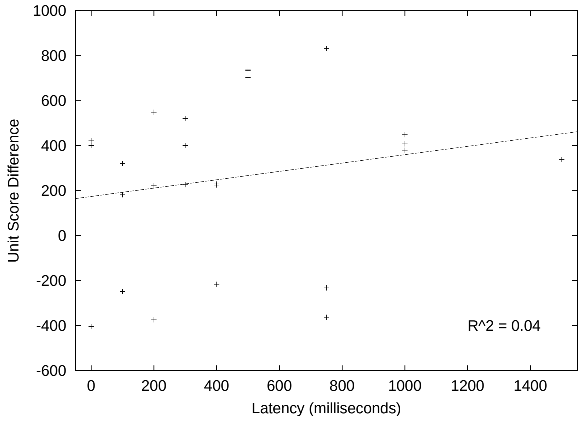

Figure 17: Age of Mythology - Unit Score Difference versus Latency.

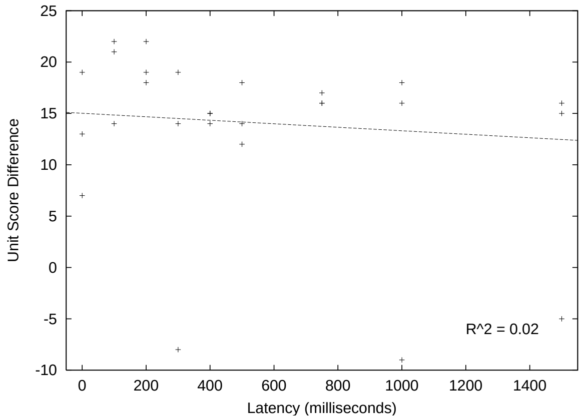

Figure 18: Command and Conquer: Generals - Unit Score Difference versus Latency.

latency is modest (0.79) for AoM, but the effect of an additional 2 seconds of exploration time for every 100 ms of latency would be insignificant in a real game. The correlation between exploration and latency for CCG is very low (0.09). Combined with the data on building in Warcraft III (Section 4.1.2), our conclusion is that latencies have no significant impact on exploration in typical RTS games.

5.1.3 Combat

Figure 17 and Figure 18 show the unit score differences versus latency for all runs, as well as a best-fit line for the data. The unit score difference is

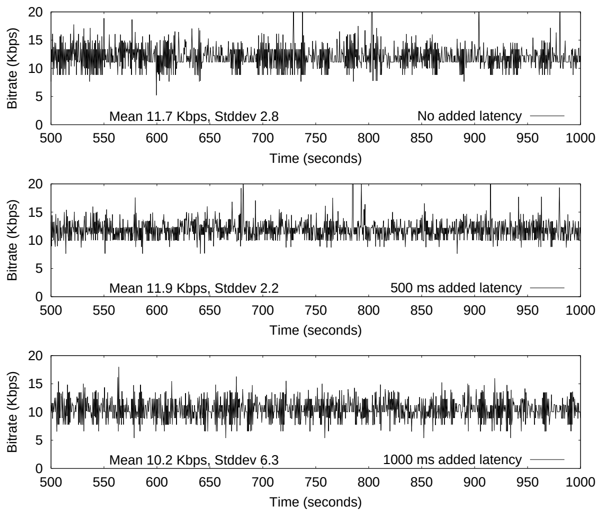

Figure 19: Age of Mythology - Bitrate versus Time.

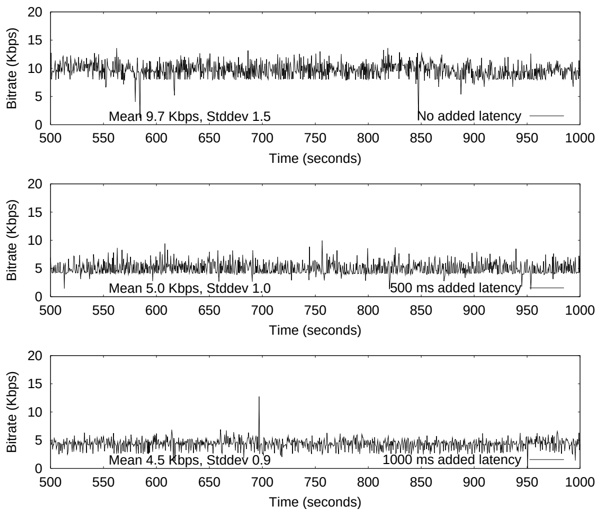

Figure 20: Command and Conquer: Generals - Bitrate versus Time.

the non-lagged player's unit score minus the lagged player's unit score. For both maps, the coefficient of determination is extremely low (0.04 and 0.02) for both combat maps. Combined with the data on combat for Warcraft III (Section 4.1.3), we conclude that latency has little effect on the outcome of combat in typical RTS games.

Overall, from our building, exploration, and combat data across three distinct state-of-the-art RTS games, we find that the effect of latency on the outcome of RTS games is negligible over the range of practical Internet latencies.

5.2 Network Level Analysis

In this section, we analyze AoM and CCG traces[18] over a range of latencies in an attempt to quantitatively determine how AoM and CCG network traffic differs with different latencies. We packet traced full games for both AoM and CCG at latencies of 0 ms, 500 ms, and 1000 ms with three games at each latency.

5.2.1 Combat Traffic and Latency

Figure 19 and Figure 20 depict the bitrate (including IP headers) taken in 500 ms intervals for the three packet traces for each game. Only the intervals 500-1000 seconds are shown to illustrate more detail, but the bitrate pattern throughout each game is similar to the shown interval. For AoM, the mean bitrate is similar across all latencies, with the variance rising slightly at 1000 ms of added latency. For CCG, however, the mean bitrate drops with an increase in added latency. All six traces have very low data rates that can easily be achieved with a dialup modem.

Figure 21 and Figure 22 depict the cumulative density functions (CDFs) of the payload sizes for all packet traces (incoming and outgoing) for each game. As for Warcraft III, the median payload sizes for AoM are all very small, around 18 bytes, with the packet size is mostly independent of the induced latency. For CCG, however, the median payload sizes are larger, around 30-40 bytes, and 5% of the payloads are over 100 bytes. In addition, the payload sizes increase with an increase in induced latency, most likely due to command aggregation at the application level.

Figure 23 and Figure 24 depict CDFs for inter-packet times (incoming and outgoing). Both games have a much more varied packet rates than does Warcraft III (Figure 11). The inter-packet times for AoM are independent of the network latency while the CCG inter-packet times increase with an increase in latency. For CCG, the decrease in pay-

[18] The Age of Mythology and Command and Conquer: Generals network traces can be downloaded at http://perform.wpi.edu/downloads/#aom and http://-perform.wpi.edu/downloads/#ccg, respectively.

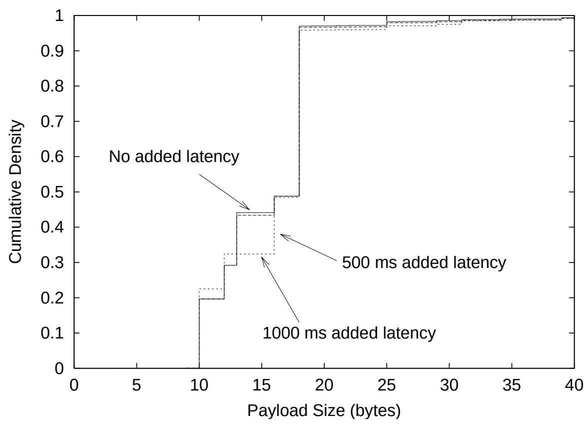

Figure 21: Age of Mythology - Payload Distributions.

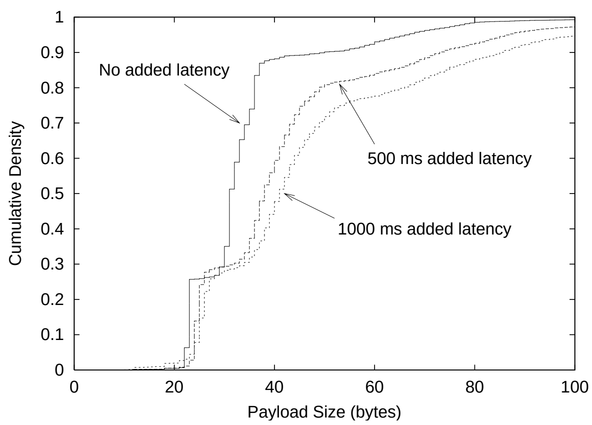

Figure 22: Command and Conquer: Generals - Payload Distributions.

load sizes with an increase in inter-packet times explains the decrease in CCG network bitrate (Figure 20) as latency increases.

5.3 User Level Analysis

For both AoM and CCG, induced latencies under 500 ms were not noticeable in that the game appeared to run smoothly. From 500 ms to about 1000 ms, the game still appeared to run smoothly, but the delays in executing commands were perceptible, although it was relatively easy to estimate this delay and react accordingly. Play was not perceptibly difficult until induced latencies were above 1000 ms.

The added latencies were most noticed in the exploration maps, especially for AoM. The triggers used in the AoM maps forced the user to stop the exploration unit by the trigger point for the induced latency amount before allowing the unit to move on. This added delay interfered with the natural movement of the unit that occurred at lower latencies.

For the combat maps, users employed slightly different strategies at higher latencies (above 500 ms) than they did at lower latencies. At lower latencies, users would often split their army into two or more groups and try to out-flank each other. However, for higher latencies it was harder to get each group to respond quickly enough for such timing-sensitive battle formations, so users kept their army in at most two or often even one group.

6 Conclusions

Understanding the effects of latency on application performance is important in order to design networks that meet application requirements. The growth in interactive network games demands better understanding the effects of latency on user performance in network games.

In this work, we investigated the effects of latency on user performance for three of the most popular Real Time Strategy (RTS) games. We divided RTS games into their fundamental components of building, exploration and combat and designed experiments to isolate and measure the effects of latency on each component.

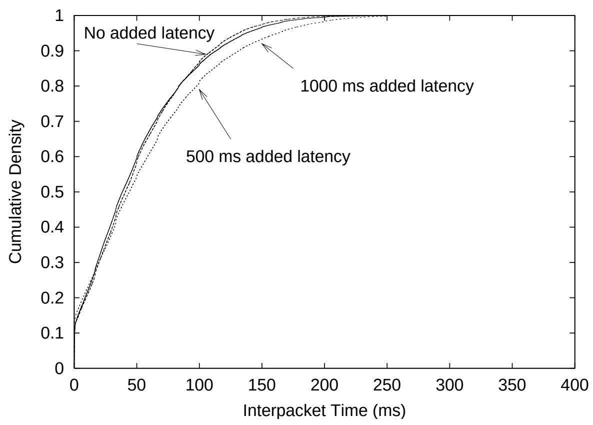

Figure 23: Age of Mythology - Inter-packet Distributions.

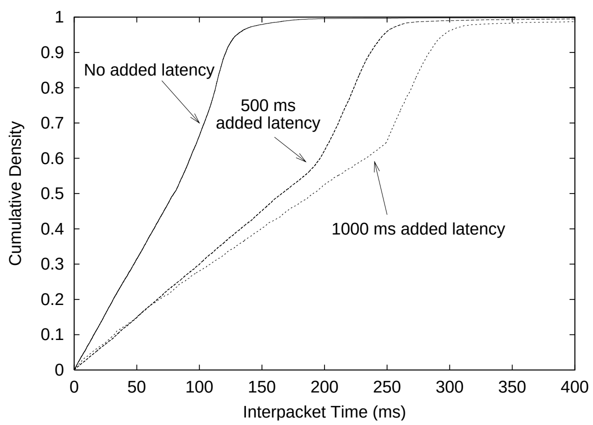

Figure 24: Command and Conquer: Generals - Inter-packet Distributions.

We find that overall user performance is not significantly affected by Internet latencies ranging from hundreds of milliseconds to several seconds. There is some statistical correlation between latency and the exploration game component, but the overall impact is minimal and there is even less correlation between latency and building and between latency and combat.

While these results are, at first glance, somewhat surprising they can be explained by the nature of RTS game play that emphasizes strategy more than the interactive aspects. While RTS games are played in real-time, reaction time plays a small role compared to understanding the game, knowing a campaign map, and having a good strategy. Since RTS user strategies take seconds or even minutes to carry out, the effects of typical network latencies (less than a second) do not impact the overall outcome. This relative insensitivity to latency is further illustrated by Warcraft III's use of TCP as the underlying transport protocol. TCP retransmits lost packets, with the retransmissions increasing application latency on the order of a round-trip time, at best, and several seconds (upon timeout) at worst. Overloading at the game server is another factor which potentially adds to game latency. The fact that many RTS games play effectively over the Internet via a centralized server further underscores the lack of significant impact of latency on game outcome.

Overall, in terms of general classification of traffic, RTS games do not have the very strict latency requirements (on the order of hundreds of milliseconds) of audio-conferencing or First Person Shooter network games, but instead have latency requirements most similar to that of Web browsing (on the order of seconds).

At the network level, RTS games basically produce small, regularly-spaced packets and modest aggregate bitrates which make it suitable for play over a low bitrate modem. At higher latencies, Warcraft III and Command and Conquer: Generals aggregate multiple commands in each packet, resulting in fewer, but larger packets. By placing multiple commands in each packet, these games somewhat amortizes the overhead of each IP header cost, thus reducing network bitrate slightly. For Warcraft III, our network analysis suggests that the aggregate of user commands sent are comparable over a range of latencies.

7 Future Work

The component-based studies presented here do not allow users to choose long-term strategies as would be present in a full game. Evaluating the effects of latency on how users choose what components to micro-manage, how they select and form long-range, even full-game strategies may provide insights beyond the results presented here.

The effects of latency on user performance in other game genres, such as First Person Shooters or Massively Multi-player Online Role Playing Games, is also still an open issue. However, it is clear that several network games consist of distinct phases which vary greatly in their interaction model and hence network behavior. The component-centric methodology presented here, which entails categorization of the game play and running of controlled users studies in each category, can perhaps be applied to these games as well, in order to increase overall understanding of network games.

Notes

I would like to acknowledge Nathan Sheldon, Eric Girard, and Seth Borg, for conducting experiments to gather the initial experimental data on Warcraft III, and YongHeng WuFang and Jonathan Glumac for conducting experiments to gather the data on Age of Mythology and Command and Conquer: Generals. I would also like to acknowledge the help of Emmanuel Agu who co-advised Nathan, Eric and Seth in the early stages of this project.

The maps used in this research and all network traces analyzed can be downloaded at http://perform.wpi.edu/downloads/#war3, http://perform.wpi.edu/downloads/#aom, and http://perform.wpi.edu/downloads/#ccg for Warcraft III, Age of Mythology and Command and Conquer: Generals, respectively.

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