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Principle and Practice of Distributing Low and High Resolution Display Content from One Computer to Many Computers in Stand-alone or Display Wall Configurations

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Abstract

Computer-based collaboration typically implies sharing display content between different display devices. This is complicated by (1) display differences, such as resolution, size, and display type, (2) different network characteristics, (3) limited network performance, (4) limited computing resources, (5) different graphical approaches, such as different architectures and graphical libraries. These complications result in the following problems: (i) there is no common cross platform and application independent solution to sharing display content across different displays; (ii) in lack of a common platform, the widely used remote desktop pixel-based approach to sharing display content does not scale well as the number of clients increases. Even with one client at typical desktop resolution, the frame rate will be limited so that users cannot get all of the shared display content. This situation will increasingly become worse as the resolution goes up.

Existing approaches to sharing display content include an application level model, a graphical level model, a pixel level model and a hardware level model. These approaches are distinguished according to the level at which display content is distributed. Applications are responsible for sharing display content in an application level model. It's dependent on the graphical library and the operating system. A graphical level model uses a graphical library to distribute display content. This is transparent to applications, but is dependent on the operating system. In a pixel level model, pixels are read from the frame buffer and distributed over a network. This is transparent to applications. It's independent of the graphical library, but not of the operating system. A hardware level model uses hardware to read and transfer pixels over a network. This is transparent to applications and independent of the graphical library and the operating system.

The characteristics of the pixel level model and its wide deployment make it realistic and interesting for further research. The VNC (Virtual Network Computing) is a widely used pixel level model. VNC uses a server-client architecture. The server encodes and transfers screen update regions in response to client update requests.

MultiStream was developed to see if the performance limitations of the pixel level model as indicated by its use in VNC can be overcome by architectural changes. MultiStream aims to let many clients view the same low resolution display content customized for each client characteristic. The idea of MultiStream is to use media streaming to share display content. There are many available compression methods for media streaming. They typically balance performance and lossyness. Media players are ubiquitous on most devices. The architecture of MultiStream has three components: (i) a video-creating producer which transforms display content into a video and streams it to the video streaming service; (ii) the video streaming service which relays customized videos to clients; (iii) a consumer viewing a video representing display content.

However, as the resolution goes up, creating videos becomes too time-consuming. So the MultiStream approach is not suited for high resolution display walls. A display wall is a distributed tiled display. Because of the display distribution and high resolution, traditional operating systems cannot directly drive a display wall. VNC has already been applied to create a large desktop to fill a wall-size tiled display. For each tile, a VNC viewer requests pixel updates for the tile from the VNC server. These updates are displayed as soon as they are received with no update synchronization between tiles. However, this desktop is too CPU- and network- intensive to achieve a high frame rate using VNC. In order to overcome this problem, several changes were done to VNC architecture and implementation. The changes include using the Intel SIMD instruction set to parallelize pixel movement, changing VNC to a multi-thread architecture and using GPUs.

A series of experiments were conducted to document the performance characteristics of MultiStream and VNC architecture and implementation for the two usage scenarios of many low resolution clients and of a single high resolution client. The experimental platform includes a 28-node display wall cluster, a video server, a server for display wall desktops and a laptop. For the first usage scenario, we measured the frame rate of 3DMark with and without concurrently encoding a video of the display output from 3DMark. We measured the CPU, memory and network load on the video server increasing the number of clients from 28 to 560. We also measured the CPU load of the VNC server, while playing back videos, increasing the number of clients from 1 to 4 for VNC. For the second usage scenario, we profiled two VNC implementations, RealVNC and TightVNC, and chose the one with the higher frame rate for further improvements. We benchmarked each improved version, playing back two videos at 3 mega-pixels and 6.75 mega-pixels on the display wall, and compared them with the chosen one.

For the first usage scenario, FPS of 3DMark is reduced by 2/3 when MultiStream encodes the display output from 3DMark. With 28 clients, the CPU load on the video server is close to 0. The CPU load with 560 clients is about 50%. With 28 clients, the memory load on the video server is less than 0.5% of the 2GB physical memory. The memory load with 560 clients is 3%. With 28 clients, the network load from the video server is about 2 MB/s. The network load with 560 clients is about 35 MB/s. With one client, the CPU load of the VNC server is about 72%. The CPU load with two, three and four clients is about 92%. For the second usage scenario, TightVNC had a higher FPS than RealVNC, so we chose TightVNC for improvement. Tuning VNC improves the frame rate from 8.14 to 10 for the video at 3 mega-pixels per frame, and from 4.3 to 5.9 for the video at 6.75 mega-pixels per frame. The improvement using a multi-thread architecture increases the frame rate from 8.14 to about 14 at 3 mega-pixels per frame and from 4.3 to about 6 at 6.75 mega-pixels per frame. When a GPU is used to copy and encode pixels, the FPS decreases from 8.14 to 1.6 at 3 mega-pixels per frame.

For the first usage scenario, the experimental result shows that the MultiStream architecture can scale to two orders of magnitude more clients than the VNC architecture. Both MultiStream and VNC are pixel level models, but their different architectures result in different performance. The reason is that MultiStream architecture separates between producing display content, capturing pixels, creating videos, and distributing videos. This allows us to use several nodes, one for distribution and another for the rest. Two different architectures result in different usages. The VNC architecture usually provides a lossless pixel stream with bad frame rates and high CPU load to support fewer viewers. In contrast, MultiStream has lossy videos for display content with good frame rates to support many viewers. So MultiStream is better suited than VNC for dynamic documents, where lossyness is acceptable, and for main clients. This can typically be the case in computer-based collaboration.

For the second usage scenario, the profiling of the TightVNC X server shows that pixel copying and encoding are the bottlenecks. This is also confirmed by the higher frame rate gained from changes done to the pixel copying and encoding, and by using a multi-threaded architecture to overlap encoding pixels between tiles. But the improved FPS is still limited. For the current implementation, using a GPU failed to improve the frame rate. This can be because of a combination of GPU characteristics including that

each GPU core is slower than the CPU doing pixel comparisons, and because of the number of cores overlapping in pixel comparisons. For practical reasons, the resolutions used in the experiments are less than 22 mega-pixels. Creating 22 mega-pixels takes too much time. Single videos are as such not suited to fill display wall with content used in experiments, and further improvements of the experimental methodology are needed. A display wall desktop using the VNC approach with a single VNC server can only support limited resolutions, although display walls are able to implement unlimited resolution. The maximum bandwidth of a display wall is subject to the minimum bandwidth of all devices, which is usually a network device. A 1 Gbit Ethernet will support about 25 mega-pixels (100 MB) per second without compression.

The MultiStream system documents that the pixel level model can support hundreds of clients viewing shared display content at a typical desktop resolution. It is VNC that limits the pixel level model. We expect that MultiStream can support thousands of clients with emerging network technology.

We conclude that, even if the VNC architecture can drive the display wall, the frame rate is bound to be low. The VNC architecture makes it impossible in principle and in practice to drive a tens of mega-pixels display wall at 25 FPS today. The VNC architecture makes it possible in principle to drive a tens of mega-pixels display wall at 25 FPS with emerging technology.

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Chapter 1

Introduction

This chapter presents an overview of the dissertation. First, hyper display and hyper-display based collaboration are introduced, as well as two problems regarding sharing display content in a scenario. Second, four approaches to sharing display content are demonstrated, and the reasons for using one of the models in the dissertation are presented. Third, the performance problems are addressed, when the chosen model is applied in the collaboration. The challenge is to design a high performance platform for hyper-display based collaboration. Fourth, the methodology is demonstrated. Finally, the contributions and organization of the dissertation are presented.

1.1 Sharing Problems in Hyper-display Based Collaboration

A ”hyper display” is a display device, where the display area is from several times to dozens of times more than the area of regular displays for personal computers; even as big as walls or larger. The increasing performance and decreasing cost of hardware for graphics acceleration makes it feasible to construct a hyper display. Hyper displays become a possible option for users. They are widely used in collaboration, research, simulation, entertainment, visualization and everyday office work. The affordable cost of hyper displays makes it possible that they can be applied in computer-supported collaborative systems, where hyper displays can implement more visualization space and improve collaboration performance.

A scenario of hyper-display based computer-supported collaboration is described in Figure 1.1, which uses a hyper display as the collaboration centre. The scenario involves many participants and multiple display devices. In this scenario, display content is an important media for communication in the collaboration. So it is important to efficiently share display content between participants and hyper displays in the scenario. Users need a way to share their display content. A hyper display also requires a way to produce high resolution display output for more visualization space. The system is required to support various networks, such as Ethernet networks and wireless networks, and various devices, such as notebooks and handheld devices. The scenario raises two problems about sharing display content:

1. How is display content shared between users?

2. How is a hyper display driven efficiently?

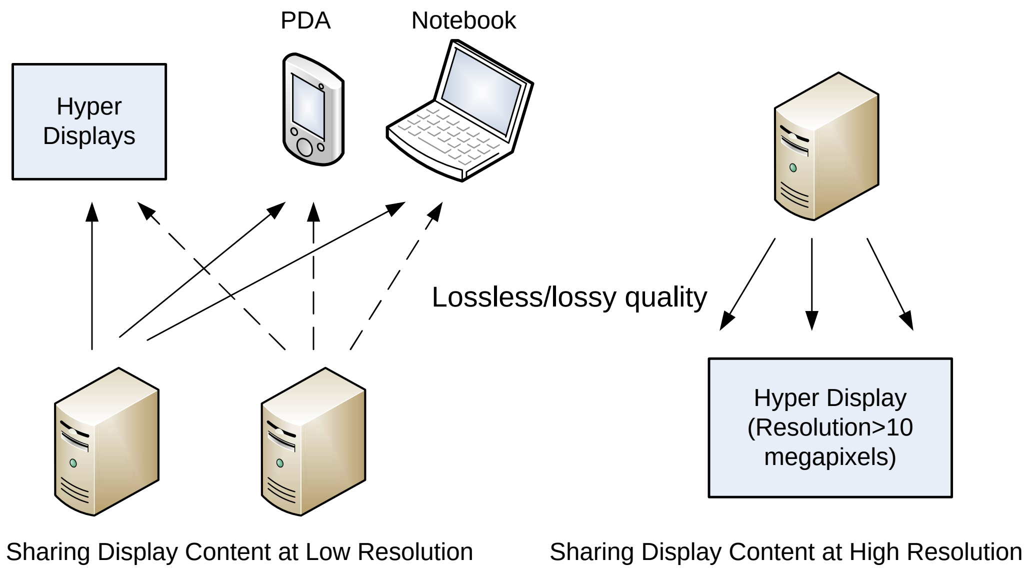

PDA
Notebook
Hyper Displays
Lossless/lossy quality
Hyper Display (Resolution>10 megapixels)
Sharing Display Content at Low Resolution
Sharing Display Content at High Resolution

Figure 1.1: Scenario of Sharing Display Content

The first problem is related to the sharing interface from low resolution displays to multiple devices. Thin clients, such as THINC [5], may be a general solution. However, the devices are required to install software to access the shared content. A more general solution is preferred, which can reuse existing applications in the devices to view shared display content.

The second problem is related to the consistent output at a hyper display. A hyper display may not be driven by a single computer directly, especially in the case of high resolution. Throughout the dissertation, high resolution is referred to as a resolution of more than 10 mega-pixels which regular computers can support. Low resolution is less than 10 mega-pixels. The limit was decided according to the resolution of IBM T220/221 [60]. One method of solving this is to drive a hyper display with multiple nodes, where each node outputs part of the hyper display.

The scenario in Figure 1.1 illustrates sharing display content to be a one-to-many sharing model at lossy and lossless quality. There are four possible combinations between low/high resolution and lossless/lossy quality. This dissertation will focus on high resolution with lossless quality and low resolution with lossy quality. Lossless quality is used to drive a hyper display at high resolution over a high speed network. Lossy quality is used to share display content at low resolution over various networks.

1.2 Existing Approaches to Sharing Display Content

In this section, approaches to sharing display content are demonstrated in a hyper-display system, before performance problems are discussed. We divide existing solutions to sharing display content into four different levels, which are shown in Figure 1.2. The approaches include *an application level model*, *a graphical level model* [22], *a pixel level model* [47], and *a hardware level model* [54]. The figure describes the level structure as well as the comparison of network performance and independence.

An application level model requires that the same copy of one application is installed on each shared

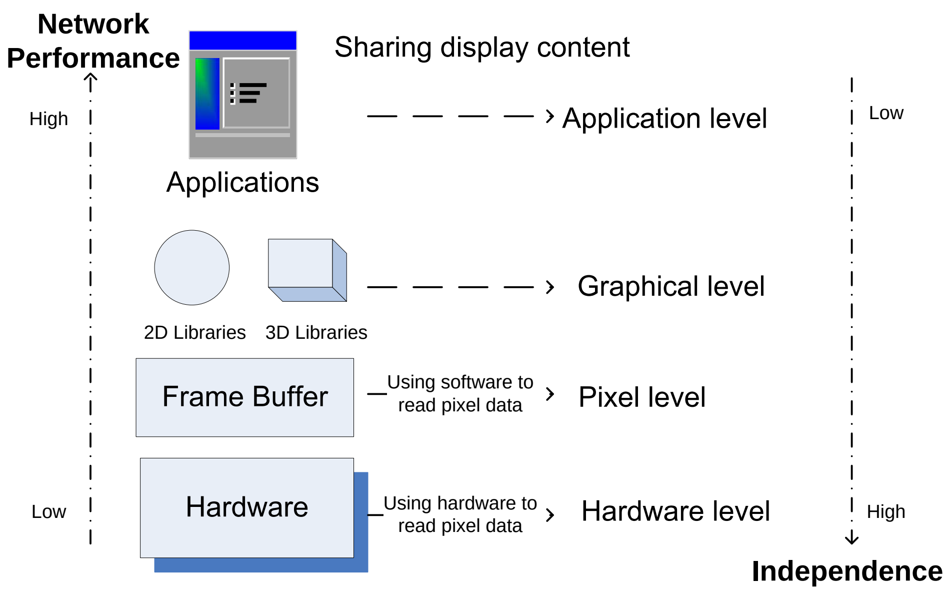


Figure 1.2: Approaches to Sharing Display Content

computational device. The devices only keep synchronized commands across a network. As a result, we can expect that there are light loads in the network and that the performance is good. However, applications can hardly support different hardware and software architectures. Rewriting applications sometimes requires access to the source code of the application. The individual copies of the application need to be synchronized, data may need to be exchanged, and user input and other I/O have to be solved on an application-by-application basis. This may be too complex and time consuming depending on the application.

A graphical level model packs and forwards 2D or 3D graphical primitives to the shared devices, where each node needs the same existing graphical libraries. The advantage of this model is that there are no modifications for running applications. The model easily supports remote 3D output. For instance, OpenGL [51] as an open source code makes it possible to render 3D visualization content into hyper display. There are many successful projects based on OpenGL, such as Chromium [22]. Applications don't need rewriting, but for some libraries, they need re-linking. The requirements of access and modification of graphical libraries makes it difficult to develop. Using OpenGL or Chromium will not by itself increase the resolution of the output from an application. To increase the resolution the application must be modified. The dependence on the specific library also limits the range of the model.

A pixel level model which gets display output from a virtual frame buffer is simple. Reading pixels and encoding them are implemented with software in this model. So it is highly independent of applications and platforms. For instance, virtual network computing (VNC) [47] is a successful case of the pixel level model, which simply puts a rectangle of pixel data at the specified position of the destination.

A hardware level model involves the use of special hardware to read pixels from the hardware frame buffer directly. The advantage is that it is completely independent of operating systems where shared applications run. The disadvantage is that special hardware is used.

Two dimensions can help us to evaluate models: network performance and independence of shared applications, as shown in Figure 1.2. Different sharing models can provide different performance and independence and fit in with application scenarios. Generally speaking, an application level model will give the best performance, and a hardware level model gains the most independence.

This dissertation argues that a pixel level model is the best one for the scenario in the hyper-display based collaboration because of high independence of shared applications and no need for special hardware. Hyper-display based collaboration needs to reuse existing applications. A pixel level model can support this better than the other methods. Since the pixel level model is independent of specific applications, the model also makes it possible to support various devices. However, the model raises CPU and network performance problems, because the model has to deal with a lot of pixels to encode and transmit over a network. We argue that these operations are CPU- and network- intensive so that CPU and network performance challenges have to be addressed in the dissertation.

1.3 CPU and Network Challenges Using a Pixel Level Model

A pixel level model makes it possible to construct a cross-platform system to share display content in hyper-display based collaboration. However, one centre node is used, because of one-to-many sharing, to display content of the node to other devices over the network. With increasing resolutions, the architecture will result in dramatically increasing demand on CPU cycles. For example, if the resolution in each frame is up to 20 mega-pixels and the targeted frame rate is 25, then about 0.5 giga-pixels per second will need to be encoded and transferred for one client. Even if those pixels are only copied once in main memory, it will consume 1 GHz when one memory copy instruction uses 20 cycles in a 64-bit Intel CPU and each pixel occupies 32-bit. About 0.5 giga-pixels per second will consume 2 giga-bytes network bandwidth per second when pixel compression is not applied. This shows that sharing display content is very CPU- and network-intensive. In that case, we need more powerful machines or better algorithms. However, the computing performance of applications cannot be gained by simply upgrading the hardware. The growth pattern of CPU performance has changed from simply relying on increasing CPU frequency. The two following laws are used to help us to understand the challenge of sharing display content in a hyper display.

1.3.1 Moore's Law and CPU Frequency

Moore's law [33] has described a long-term increasing trend of the number of transistors on a chip. It states that the number of transistors on a chip has doubled approximately every two years [23]. Moore's law implies the efficient and effective usage of the transistors. Moore's law is also useful to demonstrate the trend of the capabilities of many digital electronic devices, such as processing speed. The transistor count can sometimes reflect processing speed. The improvement of CPU frequency will lead directly to the better performance of CPU-intensive applications. The question is whether processing speed can follow Moore's law. In order to demonstrate it, the increasing trend of Intel processing speed is shown in Figure 1.3.

Figure 1.3 shows that the processing speed has doubled every two years from 1994 to 2002. The increasing CPU frequency means that CPUs can provide faster computing. One of the driving forces behind the growth is the increased computing demands of operating systems and applications [64]. Modern graphical interfaces are in need of more CPU cycles. The figure also shows that the rate of increase in CPU speed decreases after 2002. It is known that the maximum processing speed is still 3.8 GHz in 2009. It is an interesting phenomenon and it means that computing performance cannot benefit from upgrading

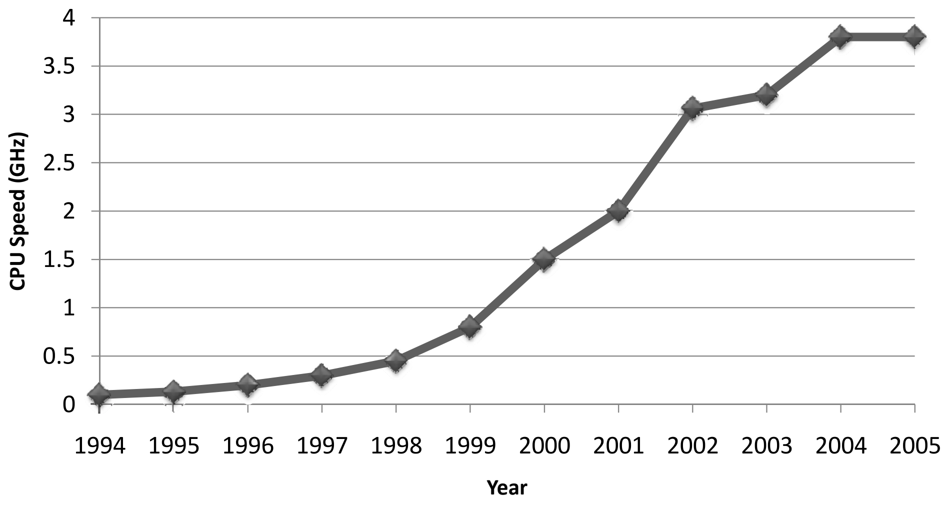


Figure 1.3: Intel CPU Speed Trend Since 1994 (Each data point shows that the CPU frequency in one year is higher than those in previous years. Source data is gathered from [31, 66].)

CPU directly now. The increasing pattern of CPU performance has changed.

Processing speeds haven't increased at the same speed as Moore's law expects. The reason is that the number of the transistors is not directly the driving force behind processing speed. Due to increased dynamic power dissipation and design complexity, it is argued that this trend of processing speed is limited with maximum CPU frequencies around 4GHz [42]. CPU frequencies Higher than 4 GHz will be unrealized. As a result, Moore's law will have almost no influence on the processing speed of one single core. The increasing transistor number is expressed in more CPU cores in one chip. The founder of startup Tilera believes that a corollary of Moore's Law is that the number of cores will double every 18 months [32]. It shows that Multi-core CPU is an inevitable trend.

It is shown that GPU has started to join in the general computing field, such as CUDA [36] and OpenCL [20]. Graphical processors have become a general-purpose computing device from a special-purpose hardware acceleration. At the moment, GPU can provide more cores in one chip than CPU. For example, there are 480 cores in GTX 295 [37]. Many-core GPU has provided another solution to improve computing performance [48, 65].

1.3.2 Amdahl's Law and Parallel Speedup

The increasing pattern of performance has changed into multiple or many cores. As a result, one application cannot benefit from multi-core CPU or many-core GPU directly. It means that applications must be aware of multiple or many cores architectures to get better performance. Applications, which stop scaling with Moore's Law, either because they lack sufficient parallelism or because their developers no longer rewrite them, will be evolutionary dead ends [28]. Sequential applications have to be rewritten to gain the improvement. Awareness of multi-core or many-core for applications will increase the complexity of program design. Even if a parallel application has been implemented, it is still a problem to know what the maximum speedup factor that we can gain is. Amdahl's law [4] is introduced in order to explain it.

Amdahl's law shows that the speedup factor of one application is subject to the sequential part. The speedup is limited even with unlimited processors. The law is used to find the maximum expected improvement to an overall system when only part of the system can be parallel. It is often used in parallel computing to predict the theoretical maximum speedup using multiple processors. The speedup of multi-core CPUs can be described with the equation as follows, where N stands for the number of processors and f stands for parallel portion.

$$Speedup = \frac{1}{(1-f)+\frac{f}{N}}$$

The limit of $Speedup$ is as follows:

$$\lim_{N\to\infty} Speedup = \lim_{N\to\infty} \frac{1}{(1-f)+\frac{f}{N}} = \frac{1}{1-f}$$

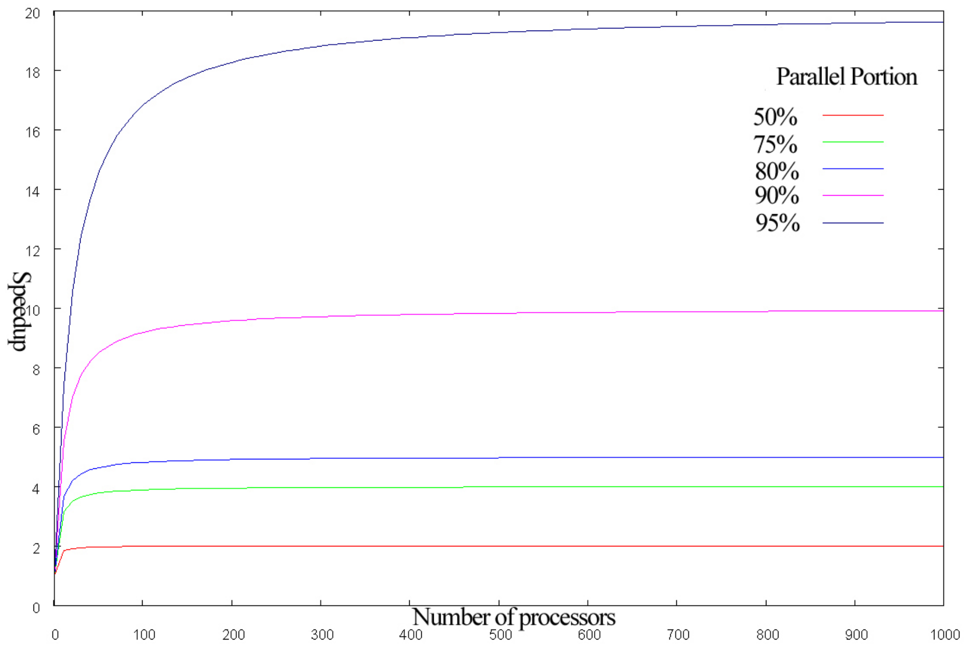


Figure 1.4: Amdahl's Law

The speedup factor can be illustrated as in Figure 1.4. When $f = 95\%$, $\lim Speedup = 20$. It shows that the maximum speedup factor depends on the parallel part of applications and the number of processors. It is difficult to get a high speedup factor. Only when the parallel portion is 100% is the speedup equal to the number of processors. Unfortunately, sharing display content in a hyper display is not that case. In our scenario, Ethernet network is a sequential part using a pixel level model. This leads to a limited speedup factor. According to our experience, speedup factor is less than 2 when a 4-core CPU is used. This law gives us the following lessons. An application has to use techniques such as multi-threading to make use of multiple cores, and the application must minimize the proportion of the sequential part. For sharing display content, the proper pixel number for tiled display will be selected carefully for better performance.

The two above discussions show that it is necessary to improve software of sharing display content for better performance from hardware. The discussions guide us to evaluate and improve the performance of a hyper display at lossless quality.

1.4 Methodology

The methodology used in this dissertation follows the process of problems, models, prototypes, evaluation and discussion. It begins with the existing problems. In order to overcome them, ideas or models can be produced from general observations. Then prototype systems are developed according to models, and experiments are evaluated to verify the models. The discussion of the results may cause new problems, which will lead to a new research cycle.

Two architectures are used to answer the two questions about sharing display content in the dissertation. One is a decentralized architecture, MultiStream, to use video streaming to share display content for low resolution clients. Clients can view shared display content with a media player. This is based on the observation that devices usually support video streaming. Another is the VNC architecture to build a high resolution desktop for hyper displays.

The experimental platform includes a 28-node display wall cluster, a video server, a server for display wall desktops and a laptop. Evaluation metrics include resource consumption, such as CPU and network usage, and performance of viewing display content, such as the frames per second that users can have.

A series of experiments were conducted to document the performance characteristics of MultiStream and display wall desktops. For MultiStream, we measured the frame rate of 3DMark with and without concurrently encoding a video of the display output from 3DMark. We measured the CPU, memory, and network load on the video server increasing the number of clients from 28 to 560. We also measured the CPU load of the VNC server, while playing back videos, increasing the number of clients from 1 to 4 for VNC. For the high resolution display wall desktop, we profiled two VNC implementations, RealVNC and TightVNC, and chose the one with the higher frame rate for further improvements. We benchmarked each improved version, playing back two videos at 3 mega-pixels and 6.75 mega-pixels on the display wall, and compared them with the chosen one.

1.5 Contributions

1.5.1 Principles

Normal Desktop Usage of VNC and MultiStream

1. For a centralized, pull-model, non-distributed architecture (such as VNC), where the applications and the encoding server are on the same node. We claim that:
   (a) Network
   It is possible both in principle and in practice for network bandwidth to support tens of clients with standard resolution desktop with emerging network technology.
   (b) Processing
   It is impossible both in principle and in practice to support tens of clients with standard resolution desktop using a single core CPU. Multi-core CPUs or many-core GPUs must be applied to achieve it.
2. A decentralized, push-model, distributed architecture (such as MultiStream), where the applications and the encoding server share the computer and where the distribution servers use multiple

computers to share display content, we claim that:

(a) Network

It is possible in principle and in practice for MultiStream using 1 Gbit Ethernet network to support hundreds of clients today, and thousands with emerging network technology.

(b) Processing

It is possible in principle and in practice for MultiStream to be handled with one single core CPU to support hundreds of clients today.

Principle for High Resolution Display Wall Desktops

The X VNC server is a centralized, non-distributed architecture. The difference compared with a normal desktop is that the resolution of a high resolution display wall desktop has more than ten times the resolution of a normal desktop.

1. Network

   It is impossible in principle and in practice to drive a tens of mega-pixels display wall desktop at 25 FPS without using compression and with 1 Gbit Ethernet network. It is possible in principle to support it with emerging network technology. It's possible in principle to support it with compression today.

2. Processing

   It is impossible in principle and in practice to drive a tens of mega-pixels display wall desktop at 25 FPS with a single core. It is possible in principle to drive it at 25 FPS with emerging technology.

1.5.2 Model

1. MultiStream model is a cross-platform solution for sharing display content over various display devices. It is designed to share display content over devices with architectural and performance differences. MultiStream model is a decentralized architecture, including live streaming producers, streaming servers and live streaming consumers. Display content is encoded as continuous video streaming, and a video server processes and distributes customized or fixed rate videos to viewers. By using standard media players and video stream formats we reduce or avoid several of these complexities and performance bottlenecks. High compression ratio and the separated server nodes improve the scalability of sharing display content.

2. VNC model is a centralized architecture to use an X VNC server desktop environment as a high resolution display wall desktop. The virtual frame buffer is in memory, which means that the resolution is only limited by available memory. Because of high resolution, the desktops are CPU- and network- intensive to achieve a high frame rate using VNC. Several changes to VNC architecture and implementation are made in order to overcome this. The changes include using the Intel SIMD instruction set to parallelize pixel movement, changing VNC to a multi-thread architecture and using GPUs.

1.5.3 Artefacts

There are four systems presented in this dissertation.

1. MultiStream: MultiStream is developed as a cross-platform sharing of display content at low resolution. MultiStream is implemented with FFmpeg [18] which is a cross-platform tool to stream video and audio. Sharpshooter is one prototype of producers implemented by us, which is developed with visual C++. Sharpshooter supports display sharing of desktop and 3D applications. Streaming server is a video HTTP server. Standard media player is used as live streaming consumers.

2. Tuning VNC: Tuning VNC is developed to improve the performance of VNC. First we profiled, measured and compared the performance of two existing implementations of the VNC model, TightVNC [63] and RealVNC [2], when playing back a 3 megapixel and a 7 megapixel video. Then we selected the best performing implementation, TightVNC, and modified it by using the Intel SSE2 instruction set to speed up data movement, and by using assembler language to speed up the encoding of the pixels.

3. Multi-thread VNC (TiledVNC): TiledVNC is developed to better adapt VNC to a display wall and improve performance over an existing implementation, TightVNC. The changes include multi-threading, a server push update protocol, and pushing updates for the same frame to all viewers. Multi-threading is implemented with POSIX threads [11].

4. GPU VNC (gTiledVNC): GPU VNC is developed to allow use of a GPU to improve the performance of VNC. Running parts of the VNC server on a GPU can potentially increase the performance by taking advantage of the highly parallel architecture of the GPU. GPU VNC has been implemented, where zero-copy buffer is used as virtual frame buffer on integrated GTX 295. Pixel encoding and the operations related to virtual frame buffer are implemented on the GPU using CUDA.

1.5.4 Claims

- A universal and simple display method using media player to display the shared content.

- A new approach to using media players to display content on display wall. Multiple output of media players can be put together into a seamless desktop.

- A new approach to evaluate performance of high resolution desktop by playing videos, where the improvement has been implemented according to the results of the evaluation.

- It is shown that high resolution desktop is presently a computing-intensive application. It uses pixel compression to reduce the requirement of network bandwidth. The bottleneck at high resolution desktop is image update and pixel encoding.

- A high resolution desktop is a highly computing-parallel application, because connections are independent of each other. It makes it possible to improve the performance of a high resolution desktop.

1.6 Organization of Dissertation

The rest of the dissertation is organized as follows.

Chapter 2: This chapter presents hardware and software for low resolution and high resolution in hyper displays. The chapter demonstrates hardware configuration of a display wall, which is one of hyper displays. The advantages and disadvantages of a display wall are discussed. Software for a display wall is introduced. A pixel level model at Tromsø display wall is demonstrated.

Chapter 3: This chapter discusses the case of sharing display content from low resolution displays to other devices. The problems of sharing display content at low resolutions are presented. The architecture of MultiStream is demonstrated, where the universal video format is used to simplify client applications. According to the evaluation results, multiple video streams are efficient to support more than 500 clients concurrently. The chapter also makes a comparison of MultiStream model and VNC model.

Chapter 4: The chapter describes how to drive a display wall as a high resolution seamless display. The architecture of a high resolution desktop is presented, based on the VNC protocol. Development platform decision is demonstrated by comparing TightVNC and RealVNC. The improvements are implemented with instruction level parallel, a multi-thread architecture, and computing using GPU. The performance of the improvement is evaluated. It shows that using a multi-thread architecture gave the best performance.

Chapter 5: The chapter discusses the research line for sharing display content. In order to demonstrate the performance problems regarding sharing display content, two models, MultiStream model and VNC model, are described. By two evaluation equations, we discuss whether it is possible to achieve sharing display content at the targeted frame rate (25 FPS) with compression or without compression.

Chapter 6: The chapter summarizes the dissertation, and the contributions are listed.

Chapter 7: The chapter lists some possible ideas for future work.

Appendix A contains the published papers, and one unpublished paper is in Appendix B.

Chapter 2

Hardware and Software for Low and High Resolution

2.1 Default Displays

A default display is related to a personal computer or a hand-held device, which is usually low resolution and small display size. Because of the difference and dispersion of default displays, a general solution to sharing display content is preferred. There is existing software for sharing display content from a default display to other display devices. For example, VNC is designed as a cross-platform protocol to share display content, which supports sharing of display content from one to many devices. The advantage is the independence and thin-client due to using a pixel level model. The disadvantage is that software has to be installed and differences between devices are ignored.

2.2 Hyper Displays

2.2.1 Introduction

A hyper display can be built with single or many monitors and projectors, including single-monitor displays, single-projector displays, monitor-based displays and projector-based displays. The first two types are usually low resolution.

LCD (Liquid Crystal Display) has become mainstream for single-monitor displays. It is possible for single display devices to create enough display area for collaboration. But it is difficult for LCD to produce hyper displays at high resolution. One of the most display sizes is 108-inch display produced by Sharp, whose display area is up to about $3.2\ m^2$ [3]. The maximum resolution of that LCD display is 1920×1080 pixels, about 2 mega-pixels. However, it is low resolution. The 108-inch LCD costs up to about $100,000. It shows that too much money is paid on low resolution. In contrast, one of the highest resolutions supported by 22-inch IBM T220/T221 [60] is up to 3840×2400 pixels. It costs about $10,000.

Single projectors can be used widely in teaching and collaboration. The types of projectors include slip projectors, video projectors, movie projectors, and so on. For computer based collaboration, video projectors are used to project the output from personal computers for other people to view. It is possible for a single projector to build a high-resolution hyper display. For example, JVC has produced a 10 megapixel 4K projector, and JVC announced a 32 megapixel 8K projector in 2008 [57]. One 4K projector costs about $150,000. The distance between screens and projectors will have an impact on image quality.

A monitor-based display is when multiple monitors are attached to one computer or cluster. A typical scenario is one personal computer with two monitors, which can be directly supported by operating systems. Now manufacturers have provided one extra monitor on notebooks. NVIDIA workstation can support multiple monitor output directly. Czerwinski [15] claimed that as many as 20% of Windows operating system users ran multiple monitors from one PC or laptop. There are also some hyper displays at high resolution using multiple monitors. A monitor-based display is created successfully with 8x3 17-inch LCD monitors, whose resolution is about 32M pixels in total [68]. However, monitor-based displays are not seamless displays.

A projector-based display is an effective and affordable way to achieve a hyper display at high resolution, using multiple commodity projectors and computers. Projectors are tiled together for a seamless display. It is scalable for projector-based displays so that it is possible to build unlimited resolutions [25]. Projector-based displays can be divided into planar displays, curved displays and dome displays [27] according to the geometry surface of a hyper display. Curved displays provide a wider field of view than planar displays [59]. They create a more immersive visual.

Much research has shown that there are some advantages of hyper displays: (1) Hyper displays can provide improvement of performance for users, such as information navigation [34, 61, 62, 68]. It is shown that performance was more efficient and more accurate because of the additional data; (2) Users can benefit cognitively from hyper displays [15]; (3) Hyper displays help to eliminate gender bias [15].

2.2.2 Display Walls

A display wall is a kind of cluster-based tiled display. Specifically, it belongs to a planar projector-based display, where the projection screen is planar. It is reported in [30] that techniques and applications were used to build cluster-based tiled displays. There are comprised of a cluster, a projector matrix and a wall-size projection screen. Each projector is driven by one node connected to one projector. A display wall is committed to construct an economic and scalable display platform, because the cluster platform uses commodity hardware at economical cost.

Projectors are physically aligned into a matrix and rear-projected onto a projection screen. The projectors are tiled into an $N \times M$ matrix, where N and M are two dimensions of the projector matrix. $N \times M$ is the total number of the projectors. The projector matrix will help to build a seamless display screen by physical position configuration of the matrix. All the projectors will project the display content from the node attached to each projector into a wall-size display. There is a software control mechanism in a display wall, by which unified display content is formed. One tile is referred to as one display area projected by one projector at the display wall. Each tile has $w \times h$ pixels, where w and h are resolutions of width and height respectively. The number of pixels of the display wall is $W \times H$ in total, where $W = (N \times w)$ and $H = (M \times h)$.

About ten years ago, it was expensive to build projector-based displays. The displays were only considered in a limited number of institutes, due to the extremely expensive infrastructure. For example, paper

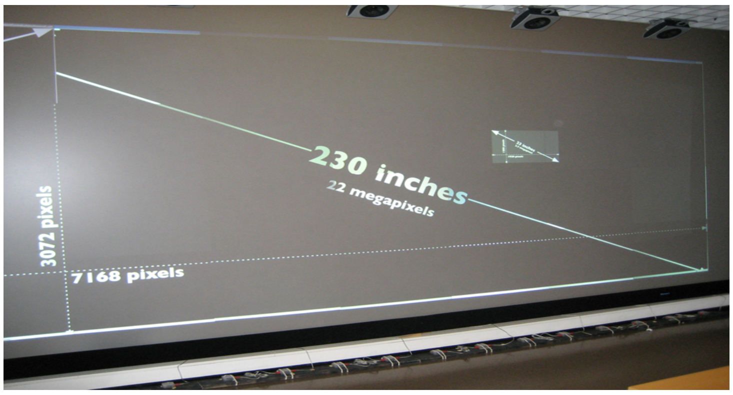


Figure 2.1: A 22 Megapixels Tromsø Display Wall

[49] presented a 2x2 tiled high resolution projector-based display wall using a pair of SGI Onyx2 visualization servers with several Tbytes of fiber-channel disk storage. Professional hardware of SGI infinity Reality would cost more $1 million. A detail cost comparison was presented between projector-based displays using professional infrastructure and cluster-based tiled displays in [7]. It is shown that it is more affordable to use cluster-based tiled displays now.

In addition to scalable resolution and lower cost, one advantage is that a cluster can make a display wall a more flexible hardware upgrade strategy. It is easy for a cluster to update some graphical cards or upgrade nodes for better performance. Each node of the cluster is usually equipped with a powerful graphical card. Those graphical cards can be used to implement parallel rendering for 3D applications.

There are some disadvantages of using a display wall. It is difficult for a display wall to automatically construct distributed projectors together and produce one uniformity of brightness and colour because of distributed tiles. However, there are some existing solutions to this. Automatic calibration [69] has been developed to reduce difficulty for the configuration of tiled display. The hyper display uses augmented projectors, where a camera is attached to each projector. Automatic calibration uses cameras to provide on-line close-loop control. Paper [8] used a special chip to produce the same illumination and colour. Another disadvantage is that a 1 Gigabit network is usually served as a cluster network and will probably lead to a bottleneck for visualization applications because the maximum network bandwidth is limited to around 100 MB.

Tromsø Display Wall

One display wall used in Tromsø is a high resolution hyper display. There are 29 nodes to together drive the display wall. 28 projectors are used to project the output from 28 nodes, and the 29th node is used as a server node in the display wall cluster. The network is a switched Gigabit Ethernet. Each node is a Dell 370s workstation, which includes Intel Pentium 4 EM64T at 3.2 GHz, 2GB RAM and NVIDIA Quadro FX 3400 with 256 MB VRAM.

The Tromsø display wall is shown in Figures 2.1 and 2.2. Figure 2.1 shows an example of the projection screen, which is equivalent to a 230-inch display device. Figure 2.2 describes a physical hardware configuration. There is a 7×4 matrix of projectors at our display wall, with 1024×768 pixels per tile giving in total almost 22 mega-pixels. The area of the display wall is 18 m^2.

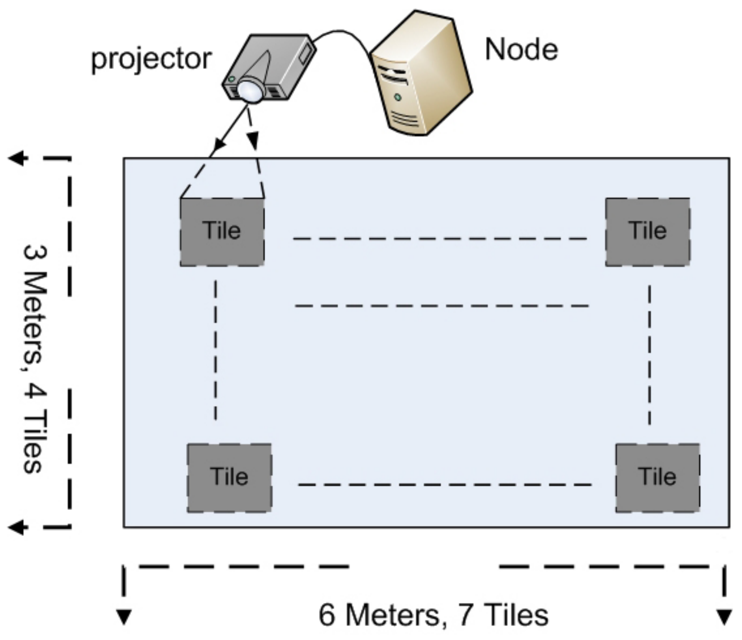


Figure 2.2: The Architecture of a Tromsø Display Wall. Each projector is plugged into a computer that displays one tile of the desktop.

Hyper Displays	Projectors	Size(m^2)	Mega-pixels	Used For
PowerWall [39]	4	4.5	8	Scientific visualization, images
Infinity Wall [14]	4	10	3	Virtual Reality
Scryer [25]	15	36	23	Stingray image API
Toronto Display Wall [6]		10	13	ScaleView
Display wall [55]	6	15	4.8	Foveal inset
Princeton Display Wall [12]	24	13.4	18	Image viewer, parallel rendering
California Display Wall [7]	9	7.4	7	High resolution images
Tromsø Display Wall	28	18	22	2D X desktop, AutoSim [1]

Table 2.1: Existing Projector-based Displays

The Tromsø display wall was built in 2004. Each node cost about NOK 15,000, and the cluster cost NOK 435,000. Each projector was Dell 4100MP projector. Each projector cost around NOK 15,000, and about NOK 420,000 was spent on display wall projectors in total. The whole display wall cost about NOK 1,000,000, or $17,000, including other devices, such as the back-projecting screen with frame. All costs occurred in 2004, and the same prices can buy higher performance hardware and build a better display wall now.

2.2.3 Software at Display Walls

The usage of a display wall includes indirect use and direct use. Indirect use refers to applications that run outside the display wall cluster, such as from personal computers. The display content is shown on the display wall. That means that an interface has to be provided at the cluster. By the interface, the display content from default displays can be shared on the display wall. In contrast, direct use means that applications run inside the cluster directly. Both of them need 2D and 3D visualization.

Due to the distribution of tiled displays, it is difficult to drive a display wall directly. There are various different application platforms on display walls for 2D and 3D visualization, as shown in Table 2.1. It shows that no standard solution to 2D and 3D visualization is available for a display wall. Each of them develops their own visualization and interaction systems.

On a display wall, 2D visualization at a pixel or hardware level can be used for both direct use and indirect use. For example on our display wall, a media player can show the display content from personal computers or the display wall.

3D visualization is one important application type, because of the large display area and many powerful graphical cards on a display wall. At a graphical level, there are two main types of 3D visualization on display walls, based on OpenGL and scene graph. Both of them can be used directly or indirectly.

OpenGL

OpenGL (Open Graphics Library) is a standard specification, which is a cross-language, cross-platform API to write graphical applications. The interface consists of over 250 different function calls which can be used to draw complex three-dimensional scenes from simple primitives. OpenGL is an immediate-mode API.

The open source makes OpenGL easy to extend applications to run in tiled displays, such as WireGL [9] and Chromium [22]. These studies can help us to extend display wall applications to 3D visualization, even for huge scenes. Our display wall desktop is currently 2D visualization. Chromium has worked with VNC viewers [45]. It is possible for our desktops to use Chromium to support 3D visualization.

Scene-graph

Scene graph is referred to as a data structure which arranges the logical or spatial representation of graphical scenes. Scene-graph will gain better network performance because geometry dataset resides at each node. The OpenSceneGraph [10] is an open source, cross-platform, high performance 3D graphics toolkit, which is written entirely in Standard C++ and OpenGL. Clustering is supported natively in OpenSceneGraph. Each node in a cluster will run a copy of scene graph data and synchronization is communicated with broadcast or multicast. AutoSim [1] is a car driving simulator system based on OpenSceneGraph. We have a visualization application using the AutoSim database in the Tromsø display wall.

2.2.4 Pixel Level Architecture on the Tromsø Display Wall

A high resolution hyper display is desired on the Tromsø display wall. We also want to reuse existing 2D applications on our display wall. These two requirements make us use a pixel level model to drive a high resolution seamless display desktop. The pixel level architecture is demonstrated in Figure 2.3, which illustrates how a high resolution display is driven by sharing pixels from a frame buffer over the network.

The secret of a high resolution desktop comes from a virtual frame buffer. A frame buffer is referred

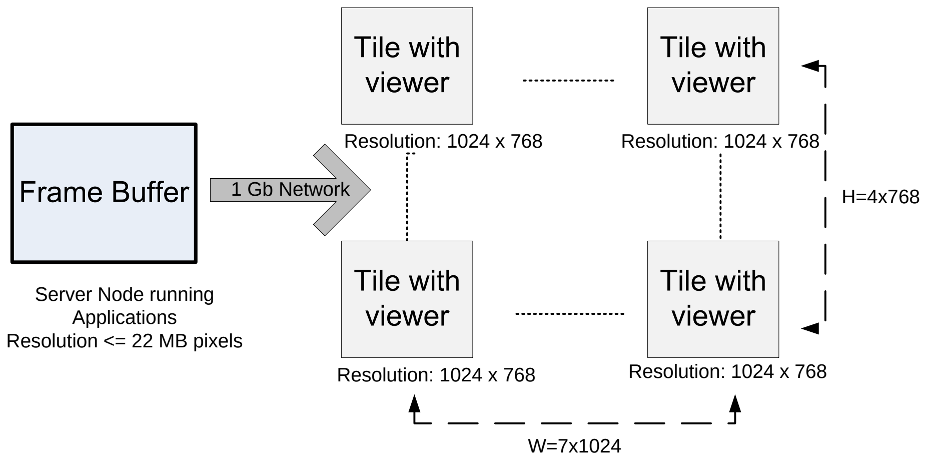


Figure 2.3: The Pixel Level Architecture for the Tromsø Display Wall

to as a video output device containing a complete frame of pixel data. A frame buffer can be a virtual device which resides in the main memory. In that case, the buffer is called a virtual frame buffer, and the resolution will not be subject to the maximum resolutions of graphical hardware. On our display wall, pixels of the virtual frame buffer in one centre node are read and transferred to the tiles on the display wall. The pixel level architecture supports the running of existing applications without modification. So the architecture is independent of specific applications. That also results in a thin viewer at the tiles, where pixels are received and displayed simply. There is no need for input from tiles.

In Figure 2.3, the resolution of each tile is fixed on our display wall: 1024×768 (0.75 mega-pixels). So the display wall with 28 tiles has 22 mega-pixels in total, and that resolution is the same as the resolution of the virtual frame buffer in the server node. The possible maximum resolution of the display wall is subject to the projectors and graphical cards. When we want to increase the resolution of a seamless display wall, the resolution of each tile and the virtual frame buffer will be adjusted correspondingly.

The implementation of the architecture is required to decide whether a pull mode or a push mode is used. A pull mode is a passive mode, and the server only responds to requests. A push mode is an active mode, and the server decides when pixels are sent to tiles.

An X VNC server is used to implement the pixel model architecture. The VNC server uses a 22 mega-pixels virtual frame buffer, where the resolution is equal to the total resolution of the tiles on the display wall. The server uses a passive request mode to respond to the request of pixel update from the tiles. Each tile only requests corresponding pixel content in the virtual frame buffer from the server.

When an application needs to produce display output to the frame buffer at the centre node, the server for sharing pixels needs a notification mechanism for update information. There are a few different ways to get information about an update on the frame buffer. When an X VNC server is used, it is simple to know update information from the related graphical primitives called when the virtual frame buffer is updated.

Chapter 3

Low Resolution Display Content Viewing By Many Clients

3.1 Introduction

With the development of hardware technology, the number and diversity of personal computational devices (PCs, laptops, PDAs, etc.) is increasing. As a result, this increased dispersion of personal devices results in an increasing need for the dynamic sharing of information and computational resources as users move between different networked environments where they want both to interact and to make use of available devices. Disks, printers, and projectors are well established examples of devices that need to be shared.

Those devices have to also be supported in hyper-display based collaboration systems, because more users start using multiple devices and the number of individual participants increases at display walls. They have a strong willingness to use their own devices to access or share information. However, although the various devices hold the requirements of different users, they also cause complexity of sharing between them. For distributed collaborative environments, there is a need also to share displays dynamically among a wide range of display resources ranging in size from PDAs to large tiled display walls.

In our own working environment we experience this need as researchers collaborate locally and remotely using personal and shared devices including laptops, PDAs, and a large tiled display wall for shared visual access. It's believed that this represents usage scenarios that offer wider applicability than just computer science researchers.

Low resolution is less than 10 mega-pixels, which is based on the resolution of IBM T220. Most personal display devices belong to low resolution. In fact, the resolutions of personal computers are around 2 mega-pixels. When one client views the shared display content at 24 FPS and 2 mega-pixels per frame, CPU cycles can support it. Memory usage can be afforded, because personal computers are usually equipped with 2 GB main memory. If the number of clients increases, sharing display content will consume more CPU, memory, and network. The scenario raises several issues:

1. Which model of sharing will support the needs for collaborative work in the environment of these

technologies?

2. What will be an adaptable architecture to support the model?

3. What is the performance of the model, such as bandwidth and scalability?

3.2 Related Work

Microsoft Remote desktop uses Remote Desktop Protocol (RDP) [13] to provide users with a remote graphical desktop. RDP, as an extension of the ITU T.120 family of protocols, is a protocol based on multiple channels. RDP supports separate virtual channels to transfer device communication data and graphical data from the server. RDP servers have their own video drivers, keyboard drivers, and mouse drivers. The protocol is to pack the graphical information and send them over the network in RDP servers. RDP clients receive graphical data and interpret the packets into corresponding Microsoft Win32 graphics device interface API calls. Mouse and keyboard events are redirected from clients to the server. It supports encrypted data of client mouse and keyboard events.

Virtual Network Computing (VNC) [47] is designed as a graphical system to support the access to the remote graphical interface. VNC uses the RFB protocol [46], which is a simple protocol for remote access with key/mouse interaction. The messages of the RFB protocol are described in Table 3.1. The RFB architecture uses the remote frame buffer protocol to implement a desktop sharing system, shown in Figure 3.1. It relays the graphical screen updates back over a network. Each VNC client is driven by event triggering. It transmits the keyboard and mouse events. However, the shared applications are required to run in VNC environments.

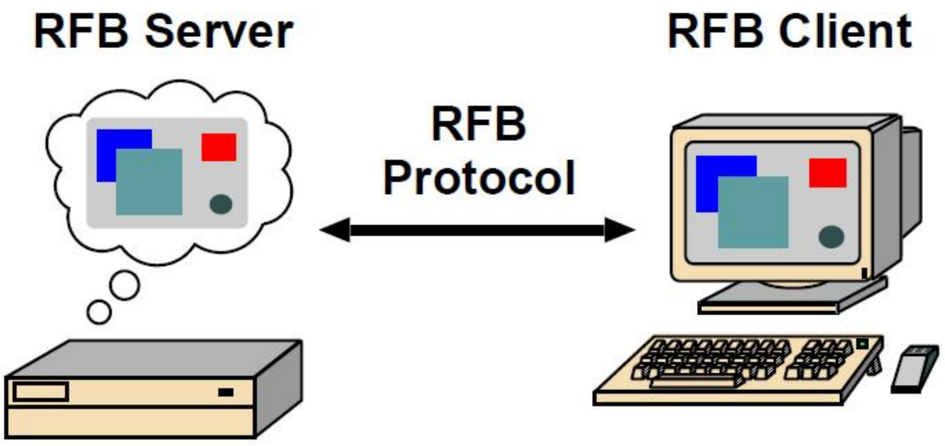


Figure 3.1: The VNC Architecture [46]

SLIM (Stateless, Low-level Interface Machine) [50] is designed as a low-level hardware- and software-independent protocol, which distributes the computational resources to users-accessible devices over a low-cost network. The SLIM architecture is comprised of the interconnect fabric (IF), the SLIM protocol, the consoles, and the servers, as shown in Figure 3.2. The IF is a dedicated connection used as a private communication medium to provide high interactive performance. The server provides computing resources to users. In addition to this, the server has daemons for authentication management, session management and remote device management. The SLIM protocol is described in Table 3.2. The console

Messages	Message Type	Description
SetPixelFormat	Client to Server	Set the pixel format
SetEncodings	Client to Server	Set the encoding types of pixel data
FramebufferUpdateRequest	Client to Server	Request a region
KeyEvent	Client to Server	A key event of a key press or release
PointerEvent	Client to Server	A pointer event
ClientCutText	Client to Server	Send the content in the cut buffer
FramebufferUpdate	Server to Client	Send the update to the client
SetColourMapEntries	Server to Client	Send the colour map
Bell	Server to Client	Ring a bell on the client
ServerCutText	Server to Client	Send the cut buffer to the client

Table 3.1: The RFB Protocol

Command Type	Description
SET	Set literal pixel values of a rectangular region
BITMAP	Expand a bitmap to fill a rectangular region
FILL	Fill a rectangular region with one pixel value
COPY	Copy a rectangular region of the frame buffer to another location
CSCS	Colour space convert rectangular region from YUV to RGB

Table 3.2: The SLIM Protocol [50]

is simply a dumb frame buffer. It receives display primitives, decodes them, and hands off the pixels to the graphics controller. SLIM was implemented as a virtual device driver in the X11 server, where all X applications can run without modification. SLIM uses the UDP/IP protocol to transmit SLIM protocol because the interconnect fabric is reliable. The experimental result shows that a SUN Ray 1 console can support a 720x480 video at 20Hz. Quake can be played at 480x360. The problem is that there is no pixel compression in SLIM, which only uses some basic compression methods, such as copy and bitmap. SLIM depends on a high reliable networking, which cannot be applied in an Ethernet network.

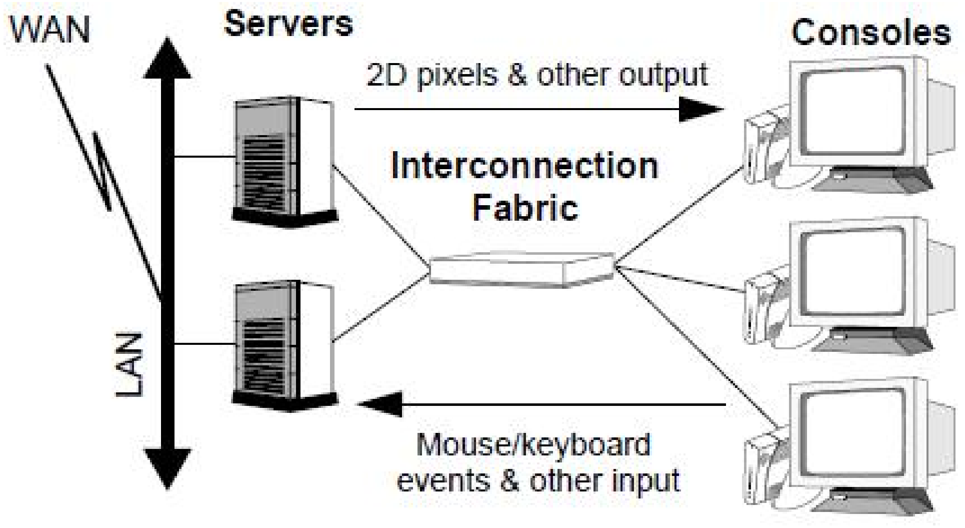


Figure 3.2: Major Components of the SLIM Architecture [50]

THINC [5] is designed as a remote display system for high performance thin-client in both LAN and

Command Type	Description
RAW	Display raw pixel data at a given location
COPY	Copy frame buffer area to specified coordinates
SFILL	Fill an area with a given pixel colour value
PFILL	Fill an area with a given pixel pattern
BITMAP	Fill a region using a bitmap image

Table 3.3: The THINC Protocol [5]

WAN networking. The THINC architecture adopts a thin-client server-push model. The server will maintain all persistent state. The server pushes the display updates only when the display content changes. The server-push method is supposed to maximize display response time. THINC is located in the video device abstract layer above the frame buffer. The translation primitives are described in Table 3.3 from display draw requests to the THINC protocol. A command queue is used for each client. The commands are distinguished between opaque and non-opaque commands in the queue. The former can be overwritten by the previous commands, but the latter cannot. The queue guarantees that there is no overlap among opaque commands. So a command has to be checked when it is inserted into the command queue. In order to protect from blocking of the server, a per-client command buffer based on the command queue is used. A multi-queue Shortest-Remaining-Size-First (SRSF) preemptive scheduler is used to flush the command buffers, where remaining size required to deliver to clients is used as the scheduler criterion. In addition to this, a real-time queue is used for the high interactivity requirement. The command buffers will be flushed in increasing queue order. THINC uses an off-screen drawing awareness mechanism. Drawing commands related to offscreen memory are tracked. The commands which affect the display are sent over networks when offscreen data are copied to the display. It also supports YUV pixel formats in order to save network bandwidth and utilize client hardware speedup. A prototype THINC server is implemented in Linux as a virtual video device driver, which can work with all X servers. RAW commands are the only commands applied to additional compression with PNG [44]. THINC uses XVideo extension to export YV12 format to application. Audio uses a virtual ALSA audio device to interpret audio data over networks. RC4, a streaming cipher, is used to improve network security.

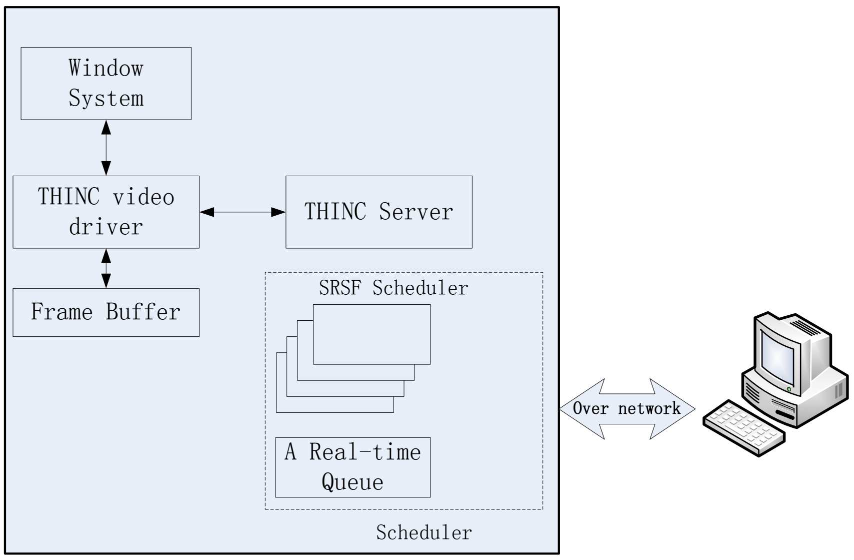


Figure 3.3: The THINC Architecture

Tarantella [53] is an adaptive Internet protocol (AIP) system, which is designed to support remote users across networks with various network bandwidth and latency. Tarantella adopts a client-server architecture, as shown in Figure 3.4. The term ”engine” in the figure refers to a process or method. The server is made up of five engines: administrative, data store, status manager, session manager, and protocol. The administrative engine is to publish applications and documents to users and manage user profile and sessions. Status manager engine, as the first engine when the system starts up, provides initialization and control of the other server engines. Data store engine is an interface to data store, which stores information regarding services, network devices, user and application data. Protocol engines are to translate standard protocols, such as X window protocol, into AIP protocol. The translation sample from X windows to AIP is given in Table 3.4. Display engine as Java applets can be downloaded on demand by clients, which renders the application onto the client displays and provides interaction for users. Sizes of display engines are usually around 200 KB, which makes display engines quickly downloadable over low-bandwidth networks. When a client accesses the web server, the boot-strap applet is downloaded on demand, which connects with the data store engine by the login applet. If authentication is successful, the webtop is given to the client. The webtop is a web desktop with different application icons. After one icon is chosen, the corresponding display engine is downloaded on demand. Each display engine will do several tests to determine display operations and display performance factor on the client display. It supports different compression methods according to this information. For example, run length encoding (RLE) is used if the request contains text or an image. If the bandwidth is less than 300 KB/s, Z-lib compression is applied.

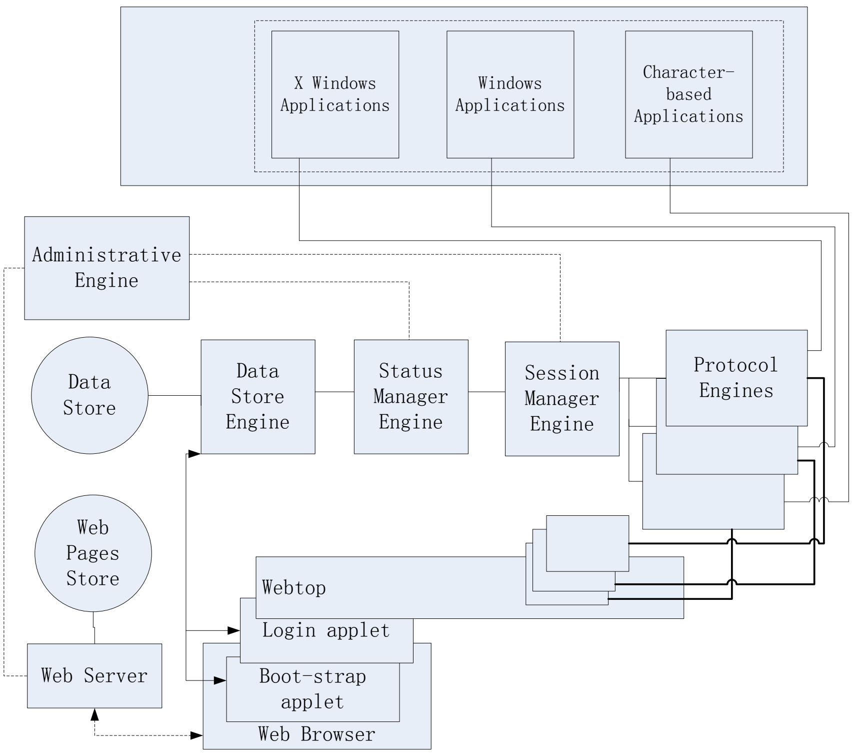


Figure 3.4: The TARANTELLA Architecture [53]

NoMachine’s NX [38] is designed as an X proxy, which can improve the performance of the native X protocol with the encryption support. The NX architecture is described in Figure 3.5. This architecture contains two NX components: NX proxy and NX agent. NX proxy is used to translate between the X protocol and the NX protocol. NX proxy supports three basic methods, compression with ZLIB, caching for X traffic and round trip Suppression. NX agent is used to avoid most round trips for the X traffic. NX uses SSH to build a secure connection between a server and a client. It provides near local speed

X11 Windows Request	AIP Requests	Explanation
ChangeGC - Set Foreground Colour Polyline	AIP_SETFG AIP_POLYLINE	Simple polyline requires only foreground colour
ChangeGC - Set dashed line style Polyline	AIP_POLYSEGMENT	Dashed lines are drawn as a series of line segments
ChangeGC - Set line width to 10 Polyline	AIP_POLYFILLRECT	Wide lines are drawn as a series of filled rectangles
ChangeGC - Set Solid Fill PolyFillRect	AIP_SETFILLSTYLE AIP_POLYFILLRECT	Simple fill request executed directly

Table 3.4: Sample Request Translations of Tarantella [53]

application responsiveness over high latency, low bandwidth links [19]. The NX proxy can achieve even a 1:1000 compression ratio.

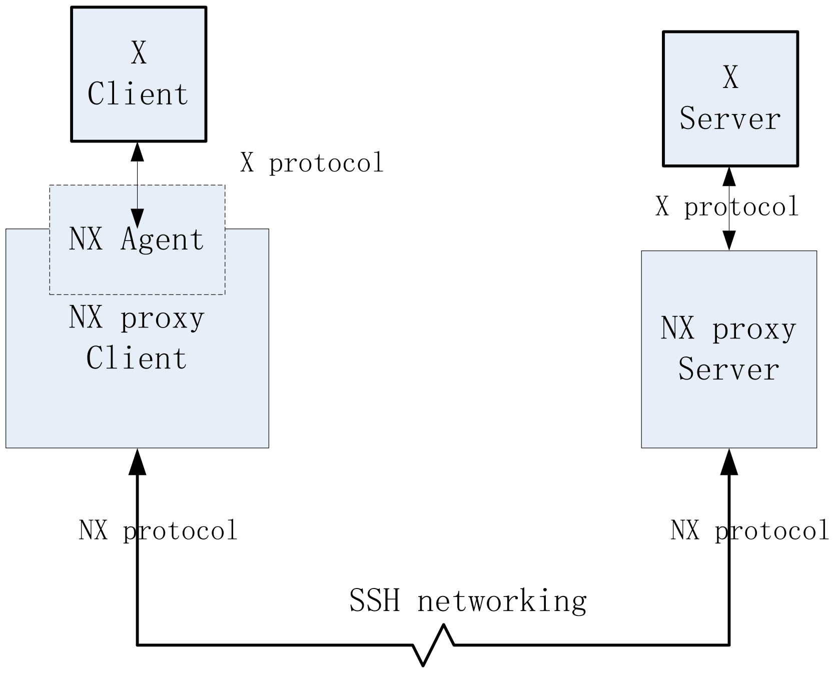


Figure 3.5: The NX Architecture [19]

Low-bandwidth X (LBX) [17, 41] is designed as an X proxy server, which provides an X environment over low bandwidth and high latency networks. An example of the LBX system is given in Figure 3.6, where a LBX server and a LBX proxy are included in the LBX system. Regular X applications access the LBX server via the proxy. The LBX architecture is described in Figure 3.7, where the X requests undergo several compression methods. One of them is short circuiting because there are small requests for unchanging information from the server, such as the predefined atom list and pixel allocation for common colours. Short circuiting will change these synchronous requests into asynchronous requests, even eliminating these requests with cached data in the proxy. By re-encoding the X protocol, the amount of data can be reduced before they are passed to a general stream compressor. One type of re-encoding is image data re-encoding, which is lossless image compression techniques used in the LBX system, such as RLL encoding for multi-bit images. The LBX server is implemented as an X extension instead of a completely new protocol of LBX. The LBX proxy uses the X server code for networking, request dispatching and authorization. Keith [40] argued that there has never been a significant effort to widely deploy it as LBX is only able to slightly improve application performance over slow network links.

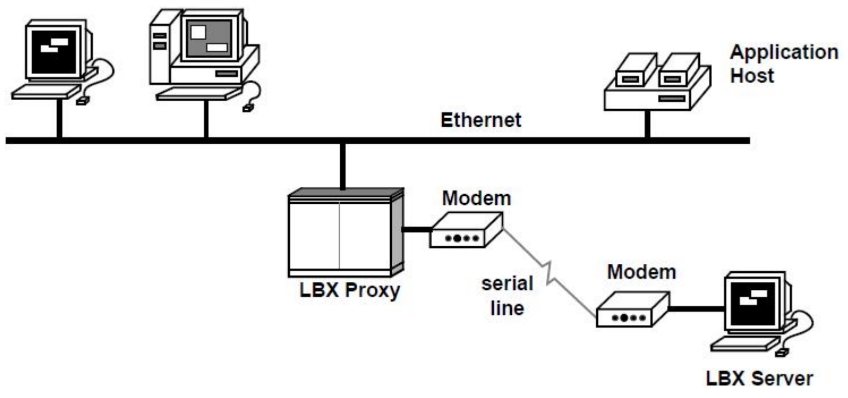


Figure 3.6: An Example of the LBX System [41]

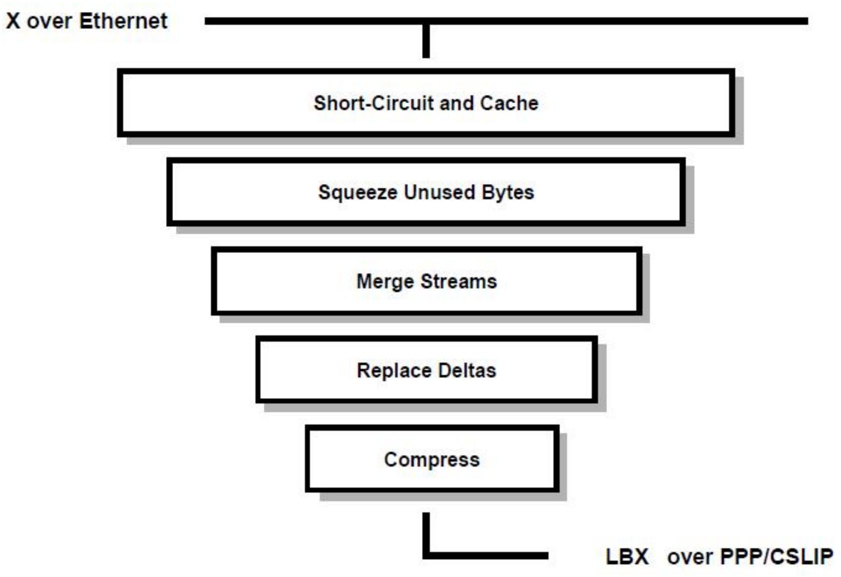


Figure 3.7: The LBX Architecture [41]

3.3 Motivation

3.3.1 Device Polymorphism

Sharing display content has another challenge in addition to the requirement of bandwidth. Most applications are designed for specific platforms. In particular, 3D applications heavily depend on graphics libraries in one specific platform, which are not cross-platform. However, there are many differences between the platforms, such as hardware and software architectures. The big differences lead to device polymorphism.

Device polymorphism refers to whether a general interface can be found to share a display in various devices. In order to explain it, the following example case is given. One OpenGL application is running in the notebook, whose operating system is Windows XP and development environment is visual studio C++. The resolution of the application is 1024×768. We want to share the output with other participants. Some of the participants are to use a display wall to watch the output, which is a high resolution (7168×3072) display and a distributed environment. At the same time, one wants to share the output with low resolution (800×480) Nokia N80 over wireless networks. But it is hard to run the application directly in the display wall cluster and handheld devices. VNC only supporting 2D primitives fails to cover that situation.

3.3.2 Scalability

The scalability of sharing display content is not demonstrated in previous research. For example, the slow-motion benchmark [35] is designed to measure the thin-client performance, which adopts the slow motions whose resolutions are 352×240 to emulate the display update. This benchmark compares the slow motion at 24 FPS with the one at 1 FPS. The following formula of video quality (VQ) [35] is used to evaluate the performance, where P stands for a specified playback rate and slow-mo stands for a slow playback rate.

$$VQ(P) = \frac{\frac{DataTransferred(P)/PlaybackTime(P)}{IdealFPS(P)}}{\frac{DataTransferred(slow-mo)/PlaybackTime(slow-mo)}{IdealFPS(slow-mo)}}$$

The assumption behind VQ is that there are enough CPU and network resources to encode pixels and transfer them over networks. The reason is that motion with 80K pixels is used. Only one client/server pair was active during any given test in the experiment [35]. That means that only one viewer is used. The scalability issue is not demonstrated at all. The same situation happens in the THINC experiments.

However, the scalability has been addressed for sharing display content. For example, TightProjector [63] is designed to project display content to many networked displays. It often happens that many clients access shared display content from networks.

3.3.3 3D applications

3D applications are a main type of visual application. Because of the design complexity and CPU intensiveness, the approaches do not support 3D applications in the related work. The support for 3D applications will extend the application range of sharing display content.

3.4 MultiStream

3.4.1 Idea

Existing Solutions

Sharing display content between various devices over networks has four different models, including *an application level model*, *a graphical level model*, *a pixel level model*, and *a hardware level model*. They are demonstrated in Chapter 1. RDP, VNC, and THINC adopt the pixel level model. Tarantella, NoMachine's NX, and LBX belong to protocols using the graphical level model.

But there is no general display sharing solution that is adopted across the range of display devices that we address. Different sharing protocols are applied between notebooks, display walls, and PDAs. For example, the virtual network computing protocol (VNC) may be used to share desktop content among PCs; while a display wall typically needs a modified VNC to distribute and share desktop content across tiles and externally. For reasons of computing and power restrictions, PDAs require other solutions. The scenario also requires that differences in network performance capabilities, display size and resolution, and graphic processing capabilities are handled. There are many applications with real-time requirements, such as 3D rendering. VNC achieves poor 3D frame rates, and effectively only supports 2D applications. In summary, achieving seamless sharing of display content across the range of devices addressed raises several issues for which there are no established answers.

Observations

In order to find a solution to device polymorphism, we try to observe the general least common denominator of sharing display content. Least common denominator means that we spend the least cost to share display content between the devices, including the support for the less powerful devices. We obtained three observations after careful examination of various devices.

1. ***Networking is ubiquitous.*** Since networks are widely used, intelligent devices usually provide networking support. Although network types provide different communication bandwidth, networking makes it possible to share display in various devices.
2. ***All computing devices understand pixels.*** The shared display is composed of pixels. Pixel data are easier to transfer over a network. There are many different formats to represent pixel data, such as image and video files.
3. ***The media player is ubiquitous.*** Most devices provide media player tools to support video streams. Media player usually supports video streaming over a network. The media player ubiquity is to provide a chance to watch shared data without extra tools. That means they have no need of extra stream client software to access shared content video streams.

Based on the above observations, the architecture of least common denominator is described in Figure 3.8. In this figure, pixel and networking have the minimum values of the least common denominator for sharing display content. Media streaming is treated as the higher value of the least common denominator, because media streaming is produced by encoding pixels. We conclude that MultiStream adopts the idea at the media streaming level. Namely, the pixels of applications are encoded into video streams over networks. In contrast with the pixel level model, which uses pixel and networking, the disadvantage is less portable because of the higher value. The advantage is that media streaming is usually supported by devices. There are many different compression methods supported by media streaming, which make sharing display content adaptable to different networks. So media streaming is the least common denominator of sharing a display across devices. According to this conclusion, the idea of MultiStream is shown in Figure 3.9.

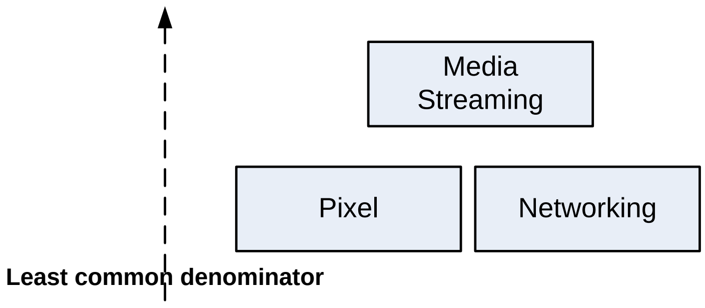


Figure 3.8: Least Common Denominator

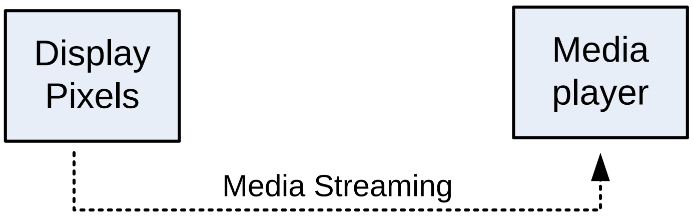


Figure 3.9: The Idea of MultiStream

We argue that this idea can address the issues in the Introduction section. The media streaming is used to address the first issue. The multiple media encoding methods can provide the adaptable architecture. It can be expected that the adaptable architecture will produce the scalable performance. This idea is called MultiStream, where multiple streams are used.

3.5 Architecture

According to our idea, the architecture of MultiStream is described in Figure 3.10, which contains three components: producers, services and consumers. One producer is used to produce shared display content of applications and encode the content into video formats over networks. Before one producer sends the shared display content to one service, the producer requests the video information from the service. After the service sends back the requested video information, the producer encodes the data according to the video information. As soon as the producer gets the pixels from the shared applications, the producer encodes the pixels into video streams and sends the video streams to the service over networks. The service provides all of the shared data. It also supports video qualities for various platforms. One consumer is a media player to watch the shared pixels. Firstly, the consumer searches all of shared information lists from the server. After the consumer chooses one shared data, the consumer sends the request to the server. Finally, the consumer can watch the shared display sent by the server over the network.

To support multiple users with a range of different devices and applications, MultiStream must capture visual content without requiring the shared applications to be modified and provide for heterogeneous clients that may require different video resolutions and encodings. To support multiple platforms, MultiStream uses standard video streams as the communication protocol to share content. Many video compression approaches make it possible to reduce network bandwidth usage.

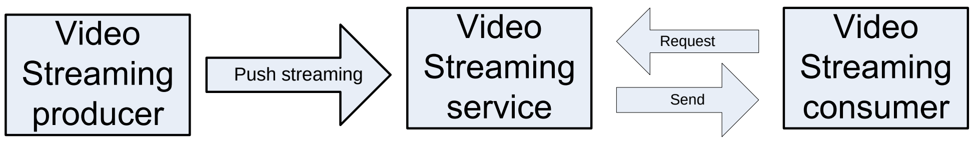


Figure 3.10: MultiStream Architecture

3.6 Design

The design of MultiStream includes three components: (1) live streaming producers, (2) streaming servers, and (3) live streaming consumers. This is shown in Figure 3.11. MultiStream adopts a server-client model. Live streaming producers include 3D application streaming producer which shares 3D applications, desktop application streaming producer which shares 2D applications or a desktop system, and other live streaming producers which share some special applications such as videos. The shared display content can be viewed from notebooks, PDAs, or display walls. There are one or more streaming servers to distribute network load. Any client connected will be redirected to a server that has capacity to serve it.

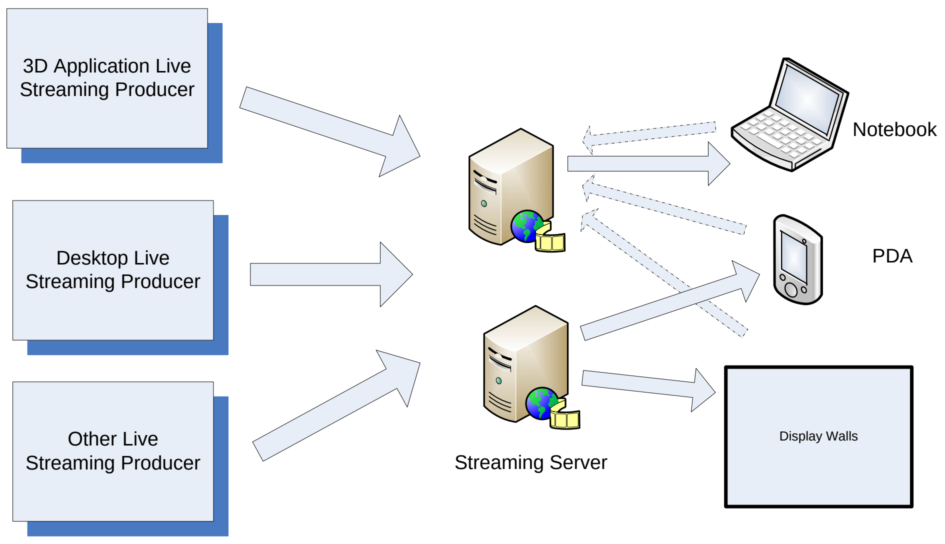

3D Application Live Streaming Producer
Desktop Live Streaming Producer
Other Live Streaming Producer
Streaming Server
Notebook
PDA
Display Walls

Figure 3.11: MultiStream Design

3.6.1 Capturing and Encoding

The goal of the live streaming producer is to produce video stream sources. The function of the producer includes capturing and encoding pixels. The producer avoids dependence on specific applications because the producer adopts the pixel model which reads pixels directly from frame buffers. Pixels are encoded into video streams and are transmitted to streaming servers. The video format is decided according to the network bandwidth. For example, PDA will use high compression video format.

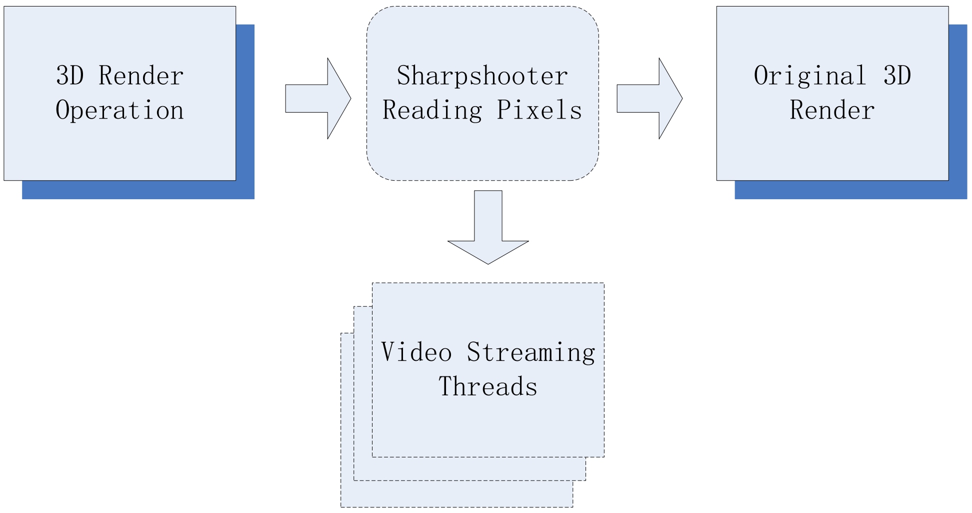


Figure 3.12: Producer on MultiStream

3.6.2 Scale Video Server

Streaming servers will receive multiple video streams from the producers and provide them to consumers over networks. Streaming servers also need to support some extra functions, such as converting between different resolutions of various devices and forwarding video streams between streaming servers in order to improve performance.

3.7 Implementation

Sharpshooter is one prototype of producers implemented by us, which is developed with visual C++. Sharpshooter supports sharing of display content of desktop and 3D applications. Sharpshooter employs Windows hooking, which is a technique using hooks to make a chain of procedures as an event handler. A hook is a point in the system message handling mechanism. When Sharpshooter starts, it registers the hook procedure which notifies Sharpshooter before activating, creating, destroying, minimizing, maximizing, moving, or sizing a window. When the system receives the window messages, Sharpshooter gains a chance to check whether the hooked application is needed to capture pixels. If Sharpshooter finds that the application is interesting, it modifies a few of the graphics library functions addresses. These functions are used to render the graphics into the frame buffer so that Sharpshooter reads the pixels data from the frame buffer when the hooked application updates the frame buffer each time. Sharpshooter sends the data to one thread, which is to encode pixels into video streams and send

Devices	Configuration
T43p	Intel Pentium M 2.2 GHz, 2G memory, ATI Mobility FireGL V3200 256MB, WinXP
Dell 370	Intel Pentium 4 EM64T 3.2 GHz, 2G memory, NVIDIA Quadro FX 3400, Rocks4.1
Cluster Network	1 Gb Ethernet

Table 3.5: The Configuration of the Devices in the Experiment

video over the network. Figure 3.12 describes the architecture of Sharpshooter. When the frame buffer is updated, Sharpshooter reads back the pixels from the frame buffer and transfers them to the worker threads to encode. Sharpshooter uses FFmpeg [18] library to deal with video/audio encoding.

We implement one scale video server with the FFmpeg library, which is an http video server. One consumer uses http protocol to access data. The server also needs to provide flexible video qualities, such as different video formats, resolutions and frame rates, in order to address the device's polymorphism. When the server finds requests from one consumer is different in video quality, the server scales the video into the requested video quality and sends the scaled video to the consumer.

3.8 Experiments and Results

3.8.1 Experiment Setup

The experiments focus on sharing display content from one computer to many viewers. The related hardware is described in Table 3.5. One producer computer is Thinkpad laptop T43p. The other PC is a Dell 370, with Linux and Rocks 4.1.

We report on the performance of a system comprised of a video producing computer with an application whose main output window is being encoded into a video and streamed to a PC (the video streaming server). The experiment setup is described in Figure 3.13. The setup includes one producer, one stream server, and 28 viewers. The network connection between the video producer (laptop) and the video streaming server (Dell PC) is a switched 100Mbits/sec Ethernet. The network between the streaming server and the clients (Dell PCs) is a switched 1Gbits/sec Ethernet.

Sharpshooter runs in T43p. The streaming server is an HTTP server. Each node will run one or more viewers. The application whose output window is encoded into a video stream is 3DMark-03, which is a benchmarking tool for the performance of 3D rendering and CPU processing (http://www.futuremark.com). The videos are played back by from 1 to 560 clients, distributed over 28 PCs. The video resolution was 320×200, 640×480, 800×600, 1024×768, and 1600×1200. Each experiment ran for 10 minutes.

3.8.2 Producer Performance

We have measured the frame rate which the 3DMark application can achieve with and without concurrently encoding a video of the frames. The result is shown in Figure 3.14. The five values on the X-axis is the number of kilobytes per frame for each of the five resolutions, respectively. Each pixel is encoded by four bytes. The y-axis is the frame rate of 3DMark. When 3DMark runs without encoding a video of its frames, the frame rate drops from about 50 to 18 with increasing resolution. When encoding is done

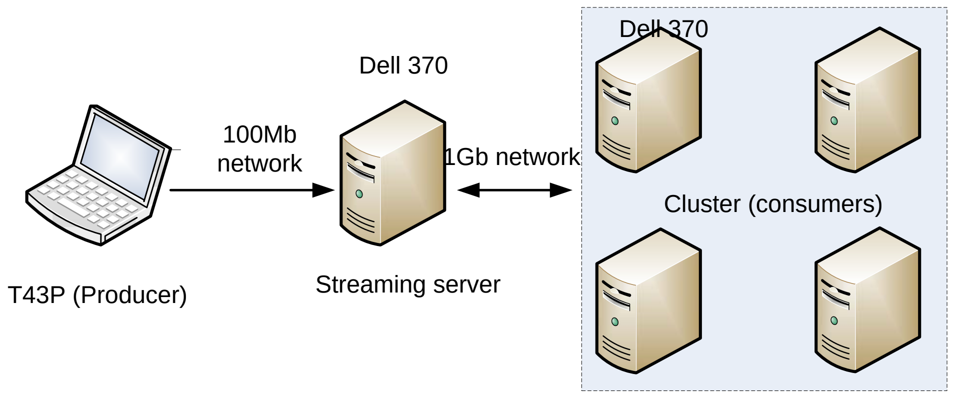


Figure 3.13: MultiStream Setup

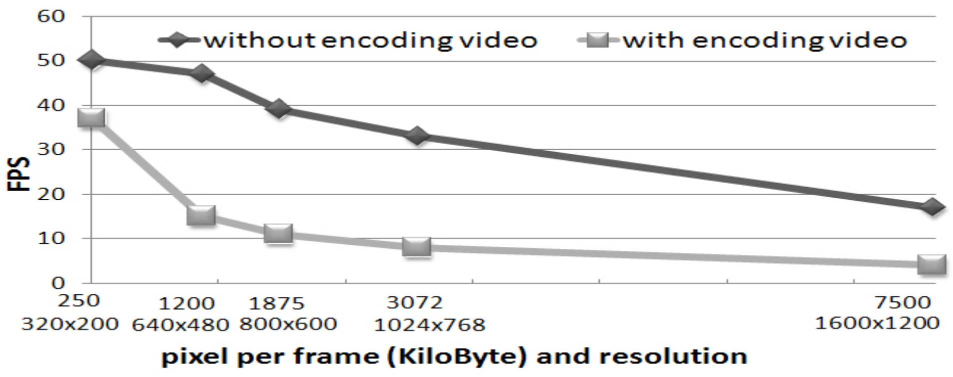


Figure 3.14: 3D-Mark FPS with/without Encoding Videos

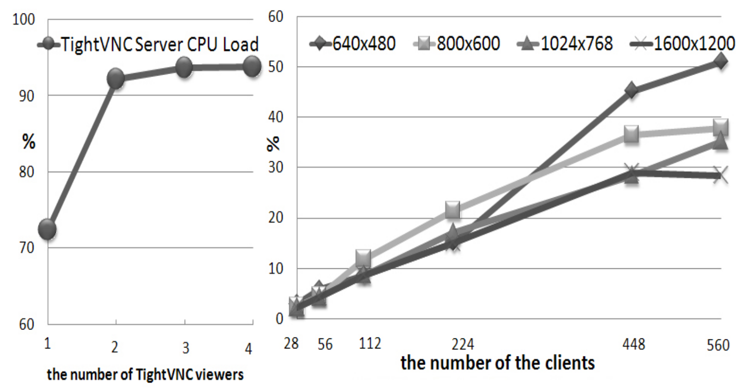


Figure 3.15: CPU Load on the Streaming Server and the TightVNC Server

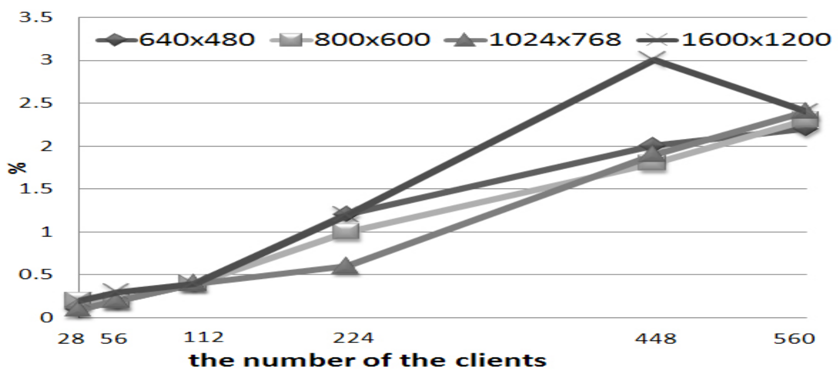


Figure 3.16: Memory Load on the Streaming Server

concurrently with running 3DMark, the frame rate drops from about 38 to 4.

The trend of FPS change is a progressive decrease in both the experiments with encoding videos and the experiments without encoding videos, when the resolution increases. The reason is that higher resolution consumes more CPU resources, which leads to the lower FPS. The FPS number with encoding videos is lower than that without encoding videos, for encoding pixels also need CPU cycles. We conclude that FPS is still acceptable, although encoding videos competes over CPU cycles with applications on the producer.

3.8.3 Scalability on the Streaming Server

To support many clients, the scalability of the video distribution server is important. We have measured the CPU, memory, and bandwidth load experienced by the server at four different video resolutions, and with the number of clients increasing from 28 to 560. The video, encoded with 25 FPS, of the 3DMark application is streamed to the video streaming server from a Thinkpad T43p laptop. The server is on a PC, and the clients are distributed over 28 PCs as explained earlier. The results are shown in Figure 3.15, 3.16, and 3.17. When the number of clients increase, the CPU load increases from a few percent to 30%-50%, depending on the resolution of the video. Lower resolutions have the highest CPU load because the frame rate is higher. Consequently, more bytes are being streamed. This can be seen when

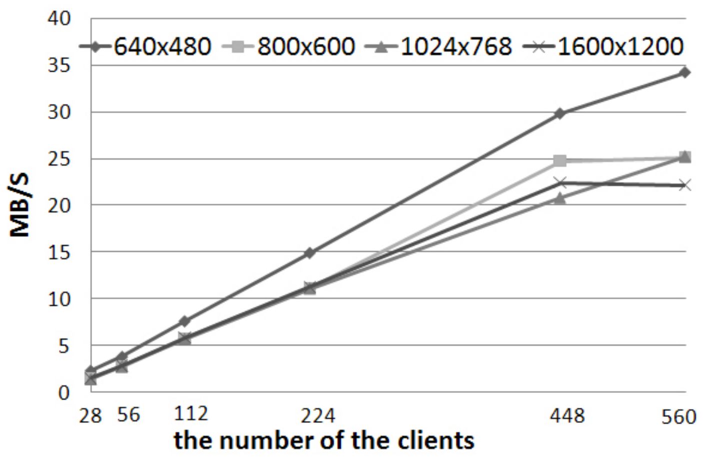


Figure 3.17: Network Bandwidth Usage

comparing with Figure 3.17, showing the network bandwidth. The memory load for a single video, even with 560 clients, is insignificant in all cases. We conclude that we, with a single streaming server, can support a realistic large number of clients. In our usage scenario, collaborative sharing of display content, we would expect approximately 5-50 clients, rather than 560.

3.8.4 Comparison with VNC

To compare the performance of VNC with our video based system, we used a variant of VNC called TightVNC [63], which uses ”tight encoding” of areas. The benchmark we use to measure the CPU load when using TightVNC is a 60 seconds long customized video with 25 frames per second, and a resolution of 1024×768. The pixels of each frame are completely different from the pixels of the next frame. We run the TightVNC server and the media player on a Dell 370 PC. We vary the number of clients viewing the video (using the TightVNC viewer) from one to four. Each client is on a separate Dell 370 PC.

Figure 3.15 shows the CPU load on the computer running the TightVNC server and the media player. With one client viewing, the CPU load on the computer running the TightVNC server is about 72 percent. The CPU load with 2, 3, and 4 clients is about 92-93 percent. The CPU load is significantly higher than the CPU load on our video streaming server. We conclude that TightVNC does not scale beyond two clients simultaneously viewing the video using the TightVNC viewer. Our system scales to over 600 clients.

3.9 Discussion

The assumption behind the idea of using videos to share display content is that for some applications and collaborative work scenarios, it is better to have lossy low resolution videos at good frame rates supporting many viewers, rather than having a lossless stream at significantly higher cost with regards to CPU load and frame rate, and with significantly fewer clients.

By building a prototype, we have documented that such video-based systems can be arranged with all the

Model	MultiStream	VNC
Architecture	Decentralization	Centralization
CPU Load of encoding pixels	higher	lower
Compression Ratio	higher	lower
Performance independence of clients	Yes	No
Impact on applications	Stable	Yes
The number of servers	≥ 2	1

Table 3.6: Comparison between VNC and MultiStream

assumed characteristics in the architecture section. The performance impact on the applications whose windows we want to share through videos cannot be avoided. Both 3D applications and the producer software are CPU-intensive. Despite the frame rate reduction experienced by the CPU and frame rate intensive applications such as 3DMark, we benefit significantly from reducing the graphics output from, at the highest resolution, 240 Mbit/sec to a streaming video of just 1 Mbit/sec. The huge added benefit of using videos are that they can be customized to, and played back on, a wide range of devices as long as a suitable media player is available.

We have not done any user studies to document if the text in documents being streamed as videos to clients is experienced by the users as ”good” or ”bad”. For our own purposes, we have no difficulties at all reading the text of documents when viewing them in a video.

A VNC server will become a bottleneck because it is one single server. Even using a single streaming server, MultiStream scales significantly better than TightVNC. However, we can support several video streaming servers to give even better scaling. The limit of MultiStream is that it lacks feedback control information, such as mouse and keyboard input. It also introduces some performance loss on producers, because producers also consume CPU cycles.

What can be learned from the nature of the differences between VNC and MultiStream? VNC is a centralization server, where applications run on the same node as the server. The application for clients is a thin client in the VNC model, and the connections for clients are independent of each other on the server. The compression ratio is usually low with lossless quality in VNC. However, MultiStream is a de-centralization server, where applications run on the node which is separated from the several servers. A complete comparison between VNC and MultiStream is shown in Table 3.6.

In Table 3.6, MultiStream adopts a decentralization architecture which has multiple servers to distribute the load, but VNC uses a centralization architecture which has only one server. CPU usage of encoding pixels in MultiStream is higher than CPU usage in VNC because of a higher compression ratio. The number of clients has no impact on the performance of producers in MultiStream. This shows that the performance of producers is independent of the number of clients. In contrast, the number of VNC clients has a big impact on the performance of the VNC server. MultiStream can have multiple streaming servers, but VNC has only one server, which runs in the same node as the applications.

From Table 3.6, the architecture from centralization to decentralization has a big effect on scalability. The decentralization architecture can support more clients. MultiStream has no negative impact on application performance with increasing number of clients, but VNC does have an impact on performance because of centralization architecture, where one centre node runs VNC server and applications. Lossy pixel compression can save more network bandwidth, because of a higher compression ratio. Decentralization architecture can use multiple nodes to support more clients for better performance.

3.10 Conclusion

We have documented through a prototype and experiments with the idea, architecture, design, and implementation, the performance characteristics of using live streaming videos to share display content. Using laptops and PCs, the performance benefit over systems like VNC is significant. Even if we have not yet documented how handheld devices and cell phones will benefit, the availability of media players on such devices and the low cost of viewing streaming videos bode well. We have designed and implemented one new display sharing system, MultiStream, which uses the pixel level model. Different from other desktop sharing systems, such as VNC, MultiStream provides video streams over a network.

The advantages of MultiStream are listed as follows:

- Media players as consumers. MultiStream utilizes media players as consumers of live display content since media players are supported by most devices and computers.
- Zero modification. The live streaming producer captures stream sources without modifications for captured applications.
- Scalability. The MultiStream system scales significantly better than using a VNC mode. It uses lower CPU and bandwidth, while supporting at least an order of magnitude more clients. In addition, the MultiStream architecture supports scalability as several streaming servers can be used.
- Adaptable. MultiStream is adaptable to network bandwidth. Video streaming supports multiple compression approaches with different compression ratios.

The disadvantages of MultiStream are listed as follows:

- The encoding of the live video will impact the CPU load of the computer running the encoding software. This will impact the performance of applications on the computer.
- There are no mouse and keyboard inputs.

Chapter 4

High Resolution Display Wall Desktops

4.1 Introduction

A display wall is comprised of distributed display tiles. A display wall desktop is used to drive a display wall. There are two requirements for a display wall desktop. One requirement is that a display wall desktop is high resolution. A high resolution desktop makes a display wall provide more visualization space and see more details. Another requirement is to keep a display wall desktop compatible with existing applications in order to simplify the use of the display wall. To keep compatible with existing applications, sharing display content is one solution from a shared traditional desktop system, such as Microsoft Windows, to each tile.

An X server using the VNC protocol (an X VNC server) is considered as a solution to meeting these two requirements. A VNC system is a simple way of creating a large enough desktop to fill a display wall. VNC uses a virtual frame buffer (VFB) to create a large desktop. VFB resides in the main memory so that the X VNC server can support a high resolution. A 100 megapixel desktop will consume 400 MB memory when each pixel uses 4 bytes. The size is usually less than the demand of main memory that a computer has. Each display computer runs a VNC viewer requesting desktop updates from the server for the region of the desktop corresponding to its tile, and displays it. VNC adopts a thin-client architecture. VNC viewers only receive pixels from a VNC server and forward interaction events to the VNC server. The architecture of a high resolution display wall desktop is shown in Figure 4.1, which is an instance of Figure 2.3, using the VNC protocol. A VNC server runs on a computer together with applications displaying onto the desktop.

When an application needs to produce output to the desktop, it uses normal X library calls to request the X server to output pixels. This call is, transparently to the application, sent to the VNC server which updates the virtual desktop correspondingly. To get updates, a VNC viewer polls the VNC server. Based on its position in the projector matrix, each viewer requests the corresponding pixel area from the VNC server. The server then, on demand, checks for updates in the desktop area covered by the requesting viewer. If there are updates, the server encodes and transmits them to the VNC viewer.

The advantage is that this architecture makes X applications run without awareness of distributed tiles of a display wall. The disadvantage is that the VNC desktop has no graphics hardware support. Consequently, encoding is done by the CPU and with the frame buffer for the virtual desktop in the computer's random access memory. Each pixel produced by the application is copied from the application's address space

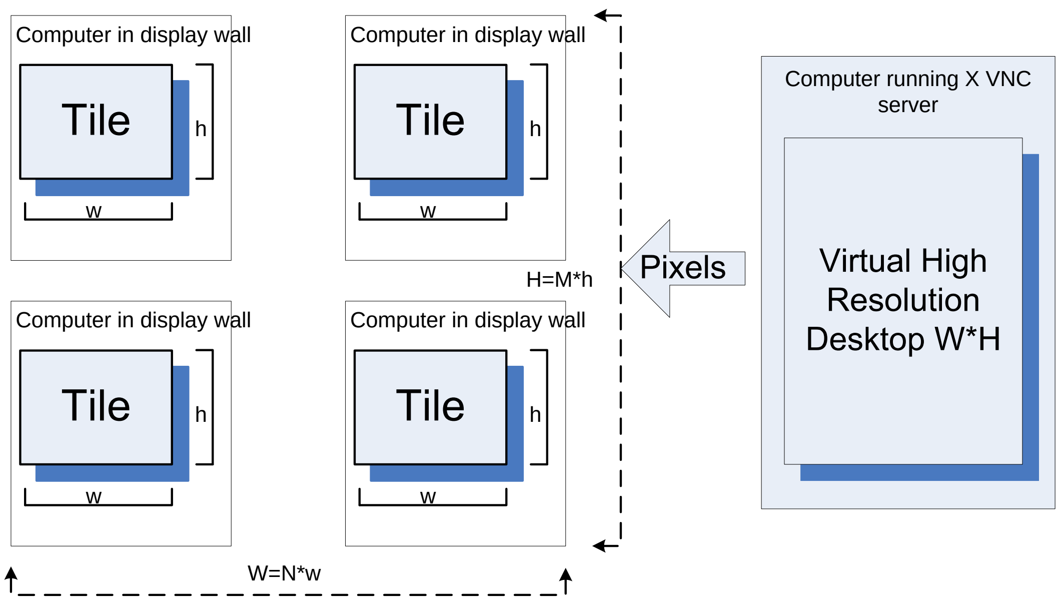


Figure 4.1: The Architecture of Display Wall Desktop Using VNC

to the virtual frame buffer in the VNC server's address space. Then it is copied inside the VNC servers address space to the encoding buffer. Using pixel compression can reduce the network traffic. However, to find out if pixels can be compressed, each pixel must be compared with a backgroud color or a given color at least once. Using the CPU and memory (instead of a graphics card) adds to the latency of X operations. Data copying and compression are potential bottlenecks when the number of pixels of the virtual desktop is increased, in particular for dynamic documents like higher-resolution videos resulting in many updates.

High resolution is defined as being more than 10 mega-pixels. In contrast with sharing display content of applications at low resolution, sharing high resolution display content needs more CPU cycles and network bandwidth. For example, when the resolution increases from 0.75 mega-pixels (1024 $\times$ 768) to 22 mega-pixels (the Tromsø display wall), the need of network bandwidth increases 28 times. It means that it is a challenge for a high resolution display wall desktop using VNC to achieve high frame rate. This chapter will focus on the improvement technologies of a display wall desktop.

4.2 Related Work

WireGL [21] is designed as a rendering system to support scalable interactive rendering on a cluster. The architecture of WireGL is shown in Figure 4.2. This architecture is comprised of three components: clients, pipeservers and a tiled display. The clients and pipeservers are connected with a high speed cluster network, such as a 1 Gigabit network. The image composition network links pipeservers and a tiled display. A single output image is produced by the image composition network. Each pipeserver can manage multiple tiles. The client is implemented as a client library to replace the OpenGL library. A run queue for each client is maintained in the pipeserver. This queue is used to pend the commands from clients. Display reassembly can be implemented with hardware (such as the Lightning-2 system [58], which supports up to 8 DVI outputs.) or software. Display reassembly in software adopts a visualization server to receive all images from the pipesevers. WireGL can sustain rendering performance over 70M triangle/s using 16 computers and 16 rendering nodes.

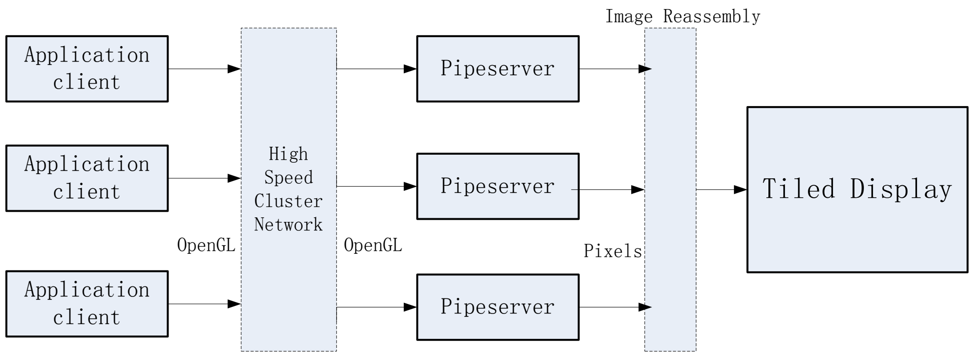


Figure 4.2: The Architecture of WireGL [21]

Chromium[22] is designed as a system for scalable rendering on a cluster, which is derived from WireGL. Chromium adopts a stream processing model, where OpenGL commands are converted into streams. Chromium introduces Streaming Processing Units (SPUs) to perform stream transformations which take a single stream of OpenGL commands and produce zero or more streams. Chromium provides some SPUs, such as render and tilesort. The render SPU is to render OpenGL commands into a window. The tilesort SPU is to drive tiled displays. An SPU does not have to implement an entire OpenGL interface. A simple chromium configuration for a tiled display is shown in Figure 4.3, where the tilesort SPU divides the frame buffer into tiles and the render SPU outputs the incoming streams into local graphical devices. SPUs are implemented as dynamically loadable libraries that provide OpenGL interface [22]. The faker OpenGL library is used to replace the standard OpenGL library. This faker library translates OpenGL commands into streams over networks.

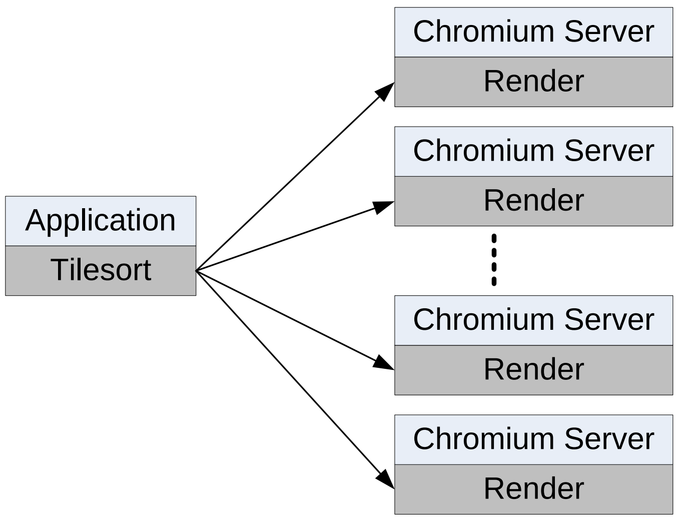


Figure 4.3: The Architecture of Chromium for a Tiled Display [22].

OpenGL Vizserver[52] is designed as an application and desktop sharing system, which distributes graphics from powerful visual servers to remote clients. Vizserver renders OpenGL remotely and transmits the rendered frame buffer to the collaborator. Vizserver adopts a server-client architecture. The architecture is described in Figure 4.4. This architecture enables X11 and OpenGL applications to be shared remotely, with machines that do not have specialist high-performance graphics hardware. When an event for a buffer swap in a window happens, the event triggers OpengGL Vizserver to read back the frame buffer of the application. After pixels are compressed, compressed data are transmitted over the networks. The client receives data, uncompresses them and outputs to the local display. Vizserver supports multiple compression approaches, such as JPEG, ZLIB and lossless compression. However, it requires applications developed with OpenGL.

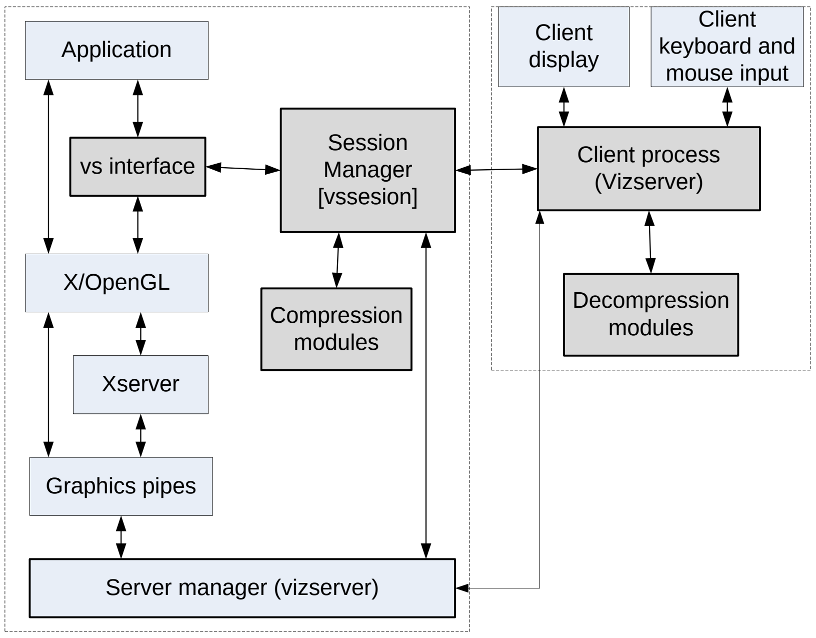

Application
vs interface
Session Manager [vssesion]
X/OpenGL
Compression modules
Xserver
Graphics pipes
Server manager (vizserver)
Client display
Client keyboard and mouse input
Client process (Vizserver)
Decompression modules

Figure 4.4: The Architecture of Vizserver [52]

Teravision[54] is designed as a scalable platform-independent display sharing system with a frame grabber card. The idea is to treat Teravision as a network-enabled PowerPoint projector. The architecture of Teravision is described in Figure 4.5. The server captures videos from the video source. The client receives video streams from the server over networks. The video data are only transferred from the server to the client. The video capture hardware is used to capture videos in the server. Network transmission supports TCP and UDP. The experimental test shows that the best performance can be up to 37 FPS when TCP is used and the video format is 1024x768 at 24 bpp. In this case, the client CPU usage is close to 100%.

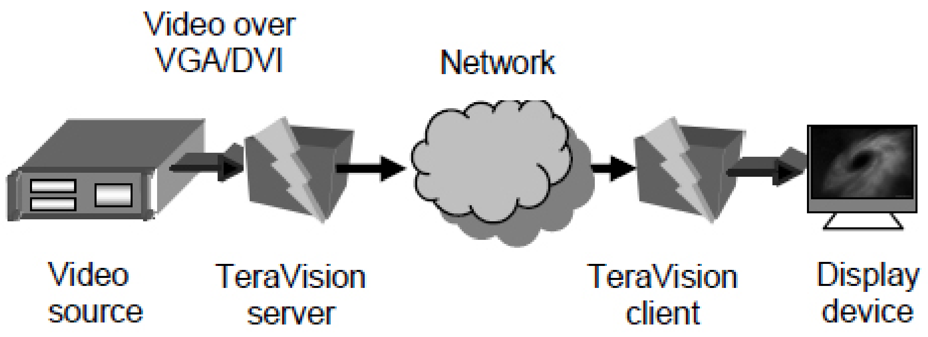


Figure 4.5: The Architecture of Teravision [54]

Scalable graphics engine (SGE) [43] is designed as a distributed hardware frame buffer at the pixel level for parallel computers. The architecture of SGE software is shown in Figure 4.6, where disjoint pixel fragments are joined within the SGE frame buffer and displayed as a high-resolution, contiguous image. Tunnel lib is to implement tunneling which transfers graphical data to SGE. The X window creation and event handling is performed in a master node, and events are distributed to other nodes with tunnel lib. The SGE is capable of updating 8 display driver cards with a peak performance of 720 mega-pixels per second [43].

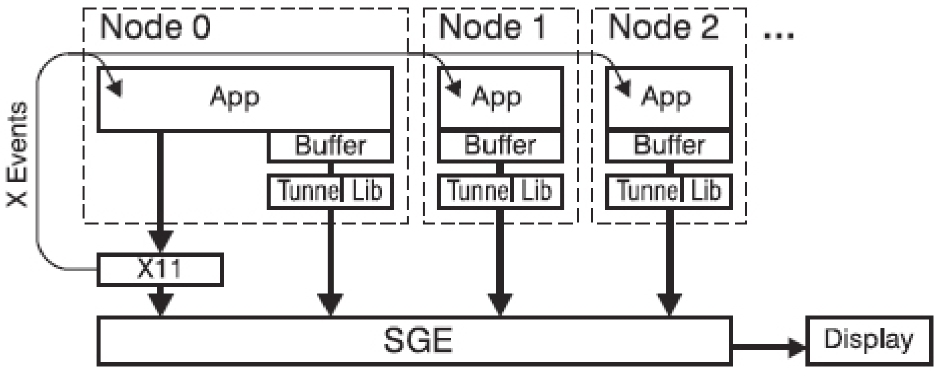


Figure 4.6: The Architecture of SGE Software [43]

SAGE[26] is designed as a flexible and scalable software approach of SGE without any special hardware. The architecture of SAGE is described in Figure 4.7. SAGE is made up of the Free Space Manager (FSManager), SAGE Application Interface Library (SAIL), SAGE Receivers, synchronization channel, and UI clients. FSManager is functioned as a window manager, which is used to receive user commands from UI clients. SAIL is an interface to the SAGE framework, which communicates with FSManager and transfers pixels to SAGE receivers. SAGE receivers are to receive pixel streams which may be from different applications. Synchronization channel adopts a master-slave model, where the master node sends synchronization signals to all nodes. After the signals are received, nodes start to render new frames when they are ready.

XDMX [16] is designed as a proxy X server, which supports multi-head X functionality across different computers. The idea of XDMX is to extend multi-head from one computer to multiple computers. The architecture of XDMX is described in Figure 4.8. XDMX includes a front-end server and a set of back-end servers. The standard X protocol is used to communicate between the front-end server and the back-end servers. The back-end servers output pixels onto the attached displays. XDMX can be used with Xinerama [67], which is an extension to the X Window System which uses multiple graphical devices in the same machine to create one large virtual display. The user will see a single unified display. It does not support pixel compression.

4.3 Experimental Methodology

A display wall desktop is implemented by sharing pixels from a remote virtual frame buffer. The update mechanism of a display wall desktop using VNC is on demand. After a viewer requests a region, the pixels in this region will be transmitted when this region is updated in the virtual frame buffer. The worst case is that the whole frame buffer is updated. As a result, the whole frame buffer has to be sent to

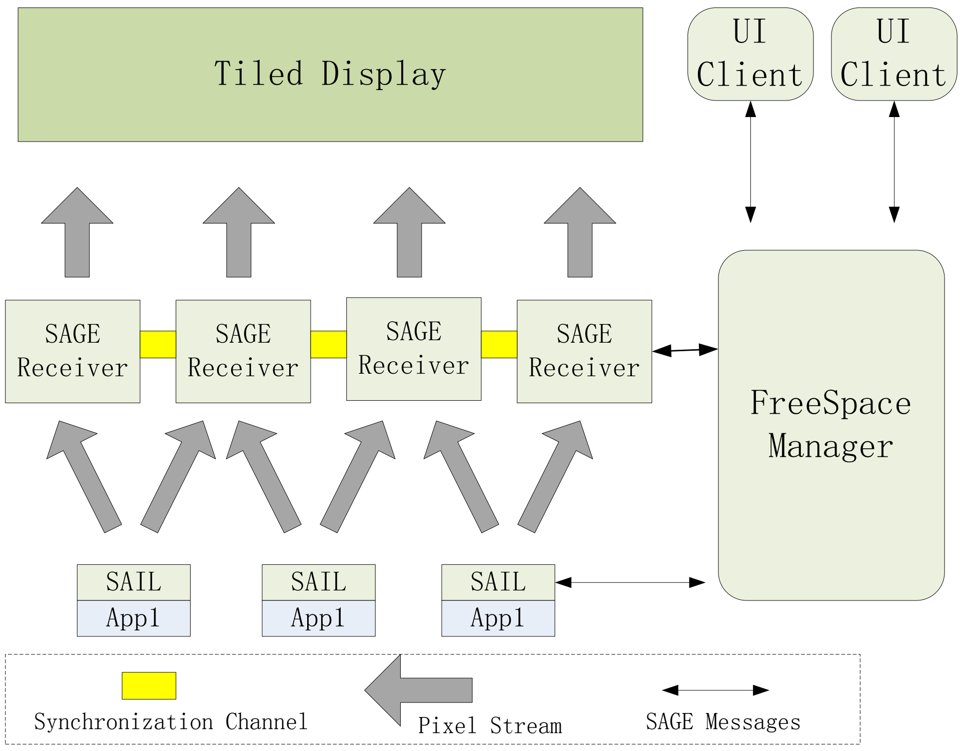


Figure 4.7: The Architecture of SAGE [26]

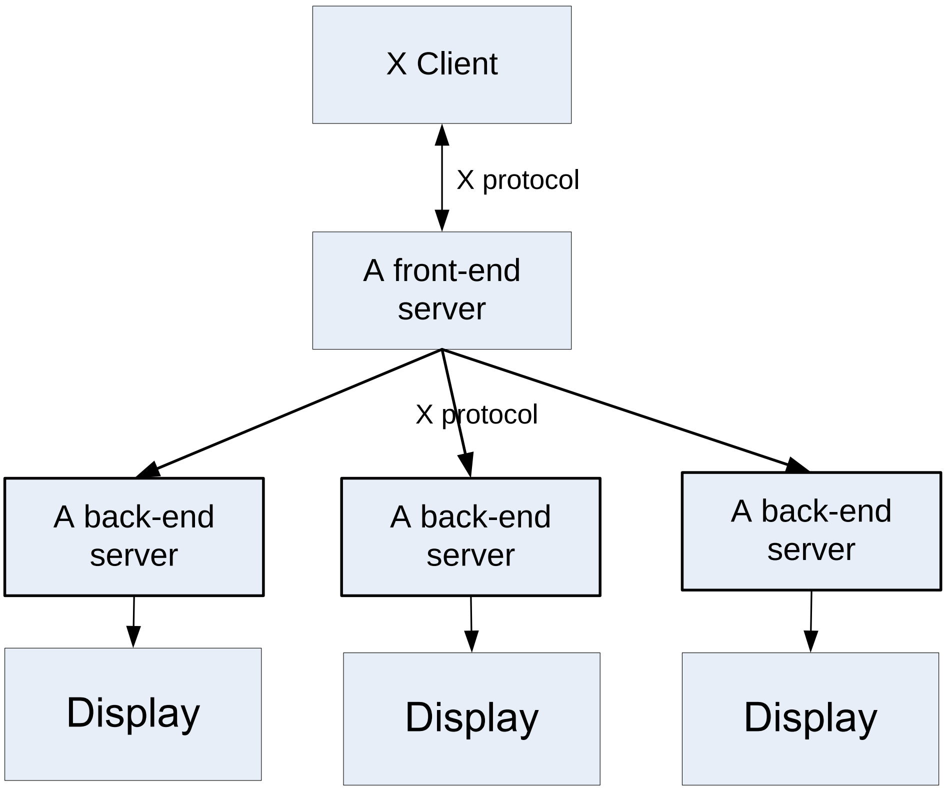


Figure 4.8: The Architecture of XDMX

viewers. In order to evaluate the performance in this case, we use playing videos to emulate the update of the whole buffer.

Two videos at 3 and 6.75 mega-pixels are used to emulate updates to a high-resolution desktop. The videos are played with a media player, one at a time, on the computer running the VNC server and are displayed to the VNC virtual desktop. The VNC viewers request updates from the VNC server as often as they can manage, and display them physically to the display wall tiles.

The two videos are made using FFmpeg [18] at the resolutions 2048×1536 (R1) and 3072×2304 (R2). The videos are encoded as MPEG4 at 30 FPS, each video lasting 120 seconds for a total of 3600 frames. The VNC server compression ratio using hextile encoding on the videos is about 5.

The R1 video covers exactly four (two by two) tiles and its area is $2.6m^2$. We assume that this area is representative of the area used by several typical streaming applications on the display wall. At nine tiles (three by three) the R2 video covers an even larger area of the display wall.

Ffplay [18] is used as the video media player. The media player runs on the same computer as the VNC server, displaying into the virtual desktop. It plays images one by one, and does not drop images because of timeouts. This is important, as the computer and VNC server cannot keep up with the 30FPS framerate, slowing down ffplay and extending the time spent on playing back the video.

For each experiment, a virtual frame buffer (a desktop) is defined at the VNC server matching the configuration of the video we play back, and at a colour depth of 32 bits. By doing this we get each video to exactly cover the whole VNC virtual desktop, avoiding complicating issues arising from having the video play back partially on more than four (or nine) tiles of the display wall.

Three performance metrics are used to evaluate performance of the VNC model for display wall desktops.

1. FPS (Frames per second): FPS is the number of updates received by the VNC viewers or by the VNC server per second. FPS represents how many frames are seen in front of the display wall. During playing videos, received frames are recorded each tile. FPS per tile is the frames divided by the playing time. While we measure and calculate the FPS per tile, we only report on the average FPS over all four or nine tiles. Higher is better. The FPS for the server is computed as the number of video frames divided by the time it takes ffplay to actually play the video.

2. UFP (Updated frames percent): The percentage of video frames played back by the media player which are seen on the display wall. The higher the UFP, the less updates are missed by the display wall. First, we count the accumulated average number of updates sent to the VNC viewers until a video finishes. We then, because each video is 3600 frames long, divide the accumulated average of frame updates by 3600 to compute the UPS. This is possible since ffplay does not drop frames, and will draw every frame on the desktop. UFP is 100% when each update is seen by all viewers, and is less than 100% when the application updates the VNC virtual frame buffer faster than the viewers get updates. The higher the UFP, the less updates are missed by the VNC viewers. Higher is better.

3. Time: This is the time measured at the display wall to play the 120 seconds long video being played back by the media player into the virtual desktop. Closer to 120 is better.

We prepare to implement high resolution display wall desktops as X VNC servers to meet the two requirements. There are several existing X VNC servers, such as TightVNC or RealVNC. TightVNC and

RealVNC are open source projects. We decide to develop our desktops based on the better one of the two, because a high resolution desktop is computing intensive. After the performance (FPS, UFP and time) is compared, we profile the chosen platform to show the bottleneck of this platform. Three improvement approaches are applied to improve the performance.

4.4 Selecting a VNC Implementation for Improvement

4.4.1 Selecting

Using videos, we did the measurements to compare TightVNC and RealVNC. Table 4.1 shows the results from the performance experiments done on TightVNC and RealVNC. TightVNC has from 1.4 to 2 times the higher frame rate than RealVNC while they both lose about 1/3 of the frames as seen by the display wall. For a user looking at the display wall, this means that the 120 seconds long video being played back into the virtual desktop, takes from 2.5 to 7 times longer to view using TightVNC, and from 3.7 to 9.5 times longer using RealVNC.

Even though TightVNC clearly has a better performance than RealVNC, it still degraded the original videos 30 FPS to respectively 8 and 4 FPS, and increased the playing time from the original 120 seconds to respectively 297 and 836 seconds. We also observe that while TightVNC has about 2 times higher FPS at 12 $MB/frame$, this is reduced to only 1.4 times better FPS at 27 $MB/frame$. Consequently, TightVNC seems to degrade faster than RealVNC when the number of pixels of the desktop goes up. Further experiments are needed to document this behaviour better.

For the highest resolution video, UFP is nearly 100%, meaning that most of the frames are indeed displayed on the display wall. This is because the VNC server now needs so much more time to prepare and send each new frame to the display wall VNC viewers that the viewers have time to send a new update request to the VNC server before the server sends its next frame. As a result, less updated frames are skipped. However, because of the server being a bottleneck, the playing time still becomes longer and the FPS decreases.

Resolution		RealVNC	TightVNC
2048x1536(R1)	FPS	4.13	8.14
	UFP	67%	65%
	Time	446	297
3072x2304(R2)	FPS	3.1	4.3
	UFP	99.6%	99.5%
	Time	1145	836

Table 4.1: RealVNC Vs. TightVNC

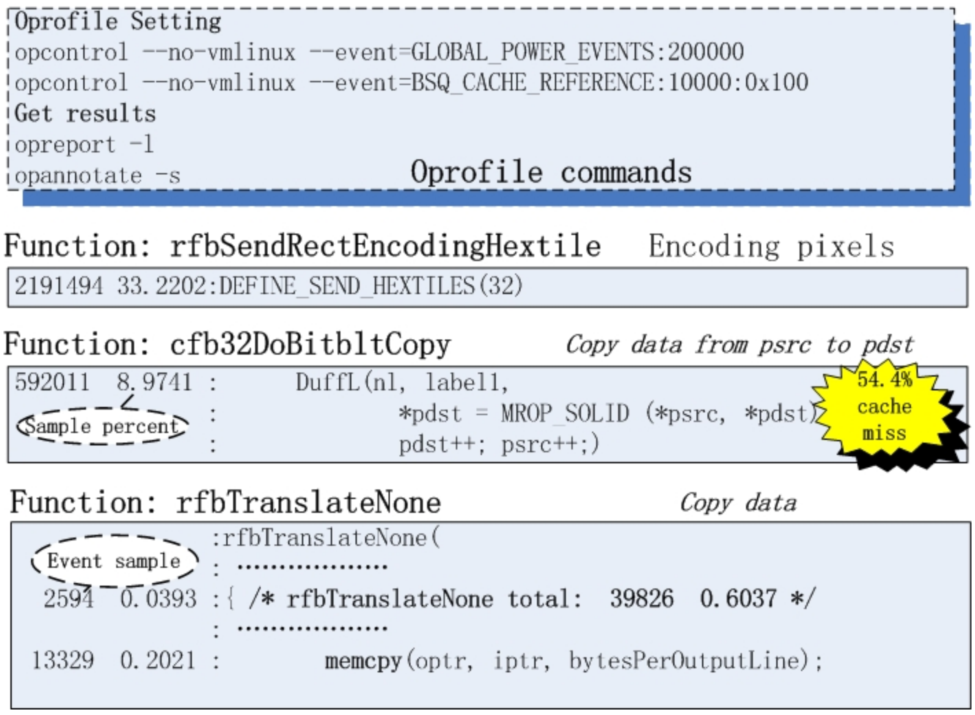
Even though TightVNC had better performance than RealVNC in the experiments we did, it still degraded the original 30FPS and 120 seconds long video significantly. Because there is no hardware support for the frame buffer of a virtual desktop, TightVNC can be expected to be both CPU and memory intensive because it needs to do a lot of both pixel copying in memory and comparisons to compress updated areas. When the pixel count increases, the CPU and memory bus loads can be expected to increase rapidly. To more precisely identify the performance limiting bottlenecks, we profiled TightVNC.

4.4.2 Profiling

Experimental Design

We profiled it with regards to CPU load distribution and the number of L2 data cache misses. Oprofile [29] was used as the profiler. Oprofile is a profiling system for Linux profiling all parts of a running system using performance counters provided by the CPU. Oprofile is low overhead in most common cases [29]. Oprofile is always running when a video is playing.

Using Oprofile, two events are focused on: GLOBAL_POWER_EVENTS (time during which the processor is not stopped) and BSQ_CACHE_REFERENCE (level 2 data cache misses). The first event type is used to find the relative CPU distribution of all running code in the computer. The second is used to find the distribution of L2 data cache misses. In Figure 4.9, the configurations of Oprofile and for the two event types are given. Before an experiment starts, we use opcontrol to set up the event types we are interested in, and after an experiment is done, we use opreport and opannotate to get the sampled event data.



```
Oprofile Setting
opcontrol --no-vmlinux --event=GLOBAL_POWER_EVENTS:200000
opcontrol --no-vmlinux --event=BSQ_CACHE_REFERENCE:10000:0x100
Get results
opreport -l
opannotate -s
```

```
Function: rfbSendRectEncodingHextile
2191494 33.2202:DEFINE_SEND_HEXTILES(32)
```

```
Function: cfb32DoBitbltCopy
592011   8.9741 :      DuffL(nl, label1,
                :               *pdst = MROP_SOLID (*psrc, *pdst);
                :               pdst++; psrc++;)
```

```
Function: rfbTranslateNone
                :rfbTranslateNone(
                : ..................
 2594   0.0393  :{ /* rfbTranslateNone total:   39826   0.6037 */
                : ..................
13329   0.2021  :        memcpy(optr, iptr, bytesPerOutputLine);
```

Figure 4.9: Critical Annotated Program Blocks

Experimental Results and Discussion

The relative CPU usage behavior and L2 cache misses for TightVNC are shown in Figures 4.10 and 4.11 respectively when playing the 2048 × 1536 (R1) video. In the figures, the only parts not directly associated with functionality of TightVNC are tagged ffplay media player, Linux kernel, libc (the C library with system calls to the Linux kernel), and (some of the) others. Even if we will not modify these, we will avoid using some of their functionality to improve the performance. The rest are measurements about the functions of the TightVNC. The function RfbSendRectEncodingHextile is used to encode pixels with Hextile encoding, cfb32DoBitbltCopy is used to copy pixels, and rfbTranslateNone is used to translate pixels between colour formats.

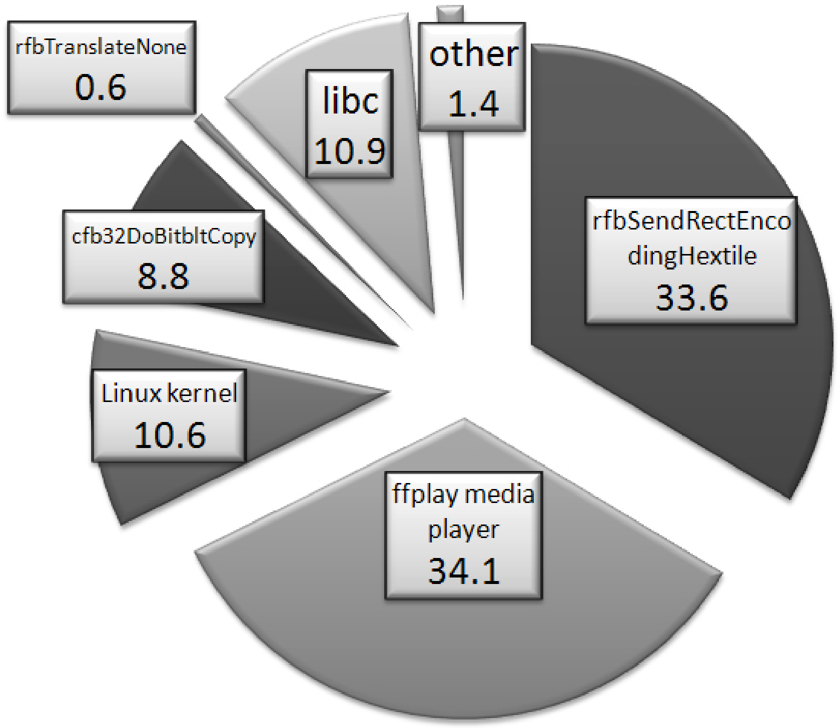


Figure 4.10: TightVNC CPU Distribution

Figure 4.10 shows that TightVNC and libc use 54% of the CPU with the hextile encoding being the single most ex-pensive part. Figure 4.11 shows that TightVNC and libc have 76% of the total number of L2 cache misses, with the pixel copying being the single most expensive part. We also observe that libc creates 21% cache misses.

Clearly, the pixel copying and hextile encoding are prime candidates for improvement. In addition the use of libc should be considered. We use the opannotate command to gain insight into the annotated source codes for these three functions. The critical program blocks that have the most number of event samples are shown in Figure 4.9. The numbers to the left under each function are the event sample count and the percentage of all events created by the function. We will focus on improving the hextile encoding, and especially to change the copy function to get rid of the high number of cache misses.

4.5 Improving the Selected VNC

According to the above profile result, a high resolution desktop is CPU-intensive. The critical codes are data movement and pixel encoding. We want to provide a smooth desktop to users, the desktop has to get enough computing resources. In order to overcome this challenge of a cluster environment, different methods of performance improvement are used, including instruction level improvement, using a multi-thread architecture and GPU computing to improve data movement and pixel encoding.

4.5.1 Instruction Level Improvement

The approach at instruction level is to use assemble language to implement single instruction multiple data (SIMD), cache prefetching and optimizing critical codes.

Data Copying

There are at least two copy operations per pixel in the TightVNC X server before an update is ready to be transmitted to the viewers of the display wall. First, pixels are copied to the in-memory virtual frame buffer of the virtual desktop. This is done by the function cfb32DoBitbltCopy. Second, pixels are copied to the in-memory encoding buffer by the function rfbTranslateNone using the libc function memcpy. The function cfb32DoBitbltCopy does the copying pixel by pixel, at 32 bits per copy. This approach results in both low memory copying bandwidth and many cache misses. The function rfbTranslateNone calls the memcpy function of libc, which also results in many cache misses. Consequently, we can expect better performance if we can improve on the copying of pixels and avoid the use of memcpy.

The Intel Pentium 4 processors support SSE2 (Streaming SIMD Extensions 2) [24]. SSE2 is one of the Intel SIMD instruction sets, which has eight 128-bit special registers and supports 128-bit operations. If we copy 128 bits at a time instead of 32, we can expect four times improvements in the copying performance. However, a memory operand of SSE2 instructions must be aligned on a 16-byte memory boundary so we must align the virtual frame buffer and the encoding buffer accordingly. Instead of using memcpy in rfbTranslateNone, we use two MOVDQA instructions to copy 128 bits at a time from the source to the virtual frame buffer.

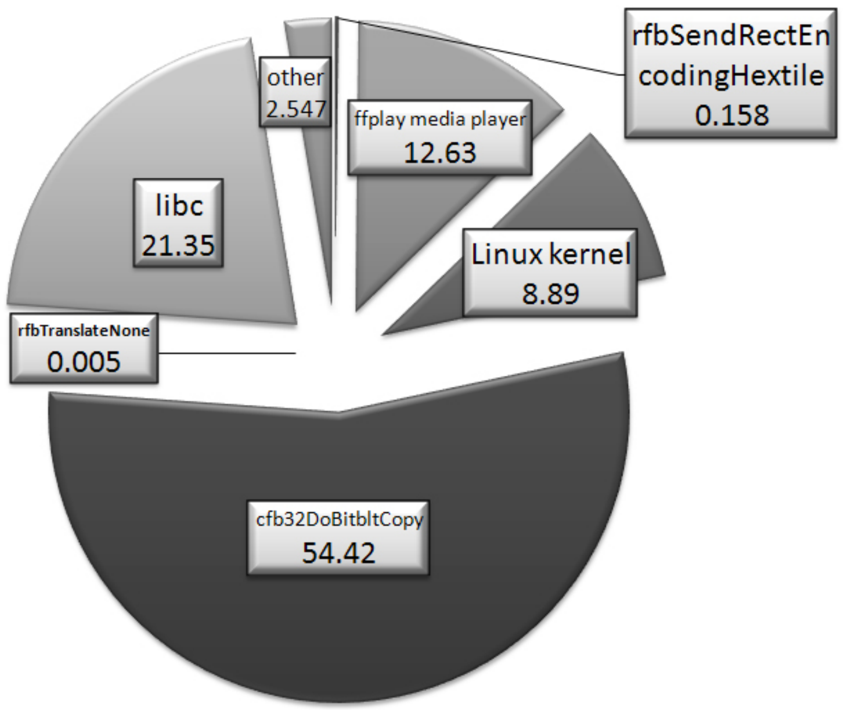


Figure 4.11: TightVNC L2 Cache Miss

We observe that for the function cfb32DoBitbltCopy, the pixel data are not needed immediately. Therefore to copy data we use the instruction MOVNTDQA because it writes data directly to memory without touching the cache, potentially resulting in fewer cache misses. To prepare the L2 cache for use we apply the instruction prefetchnta which does prefetching of data to the L2 cache. We have done all of the improvements using assembler language to have better control over what is actually taking place at run-time.

Hextile Encoding

We improve on the TightVNC pixel encoding using several techniques. First, we do some tightening of the code, meriting no further comments. Second, the hextile encoding used in TightVNC divides updated areas into pixel blocks and encodes the blocks one by one. The size of each block depends on how large the updated area is. Instead, we propose to statically divide updated areas into fixed 16x16 pixel blocks. We save by not having to access memory to find the width and height of the pixel blocks. Third, where appropriate, we replace multiplication instructions by add and shift instructions. Forth, where appropriate, we replace data branch instructions with the Intel conditional MOVCC instruction.

Fifth, we remove some branch instructions altogether. The hextile encoding implementation in TightVNC will, when having two overlapping pixel blocks of the same colour but of different sizes, choose the largest pixel block in order to get the best compression. However, in most cases, the pixel block that is biggest is the ”vertical” block. Therefore we remove the branch instructions needed to decide and statically always choose the vertical block. In practice, the compression ratio remains the same, but the compression becomes slightly faster.

Experimental Design

The hardware and software platform is a display wall comprised of a single computer running the improved VNC server and the media player, and twenty-eight computers running a VNC viewer each. Each of the twenty-eight computers has a projector attached. All computers are Dell precision 370 PCs, running 32-bit Rocks/Linux 4.1. The network between the nodes is a 1 Gigabit switched Ethernet. FPS, UFP and time of the improved VNC server are evaluated.

Experimental Results and Discussion

Video Resolution		TightVNC	Improved VNC
2048x1536(R1)	FPS	8.14	10
	UFP	65%	65%
	Time	297	232
3072x2304(R2)	FPS	4.3	5.9
	UFP	99.5%	99.5%
	Time	836	608

Table 4.2: Results of Improved VNC

After applying the changes to TightVNC, we did the previously described experiments again, this time using the improved version of VNC. The results are shown in Table 4.2. The modifications have improved the frame rate by 23-37%, while the playing time has been shortened by 22-27%. At the same time, the improved version does not lose more frames than TightVNC. Figure 4.12 shows the relative CPU distribution of the improved VNC. The improved version uses almost 10% less of the CPU vs. TightVNC, leaving more CPU cycles for applications.

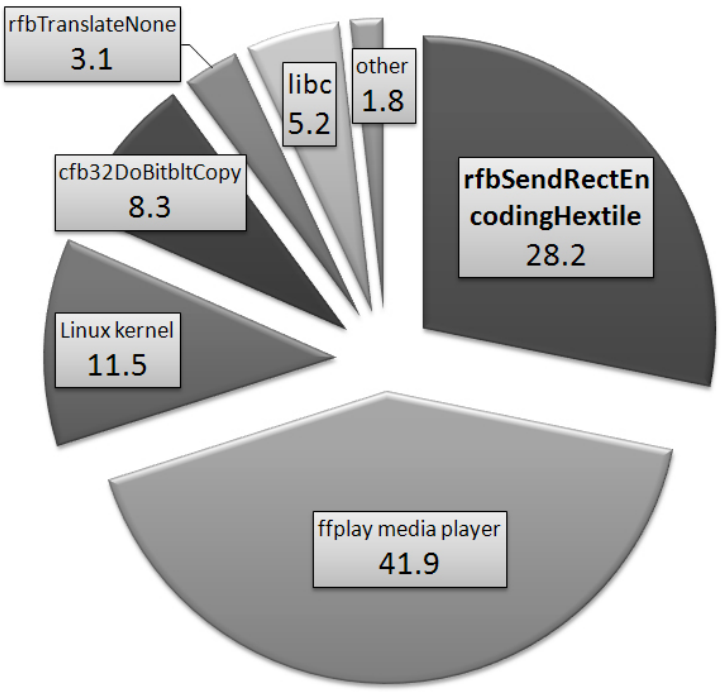


Figure 4.12: Improved VNC CPU Distribution

Figure 4.13 shows the cache misses for the improved version. The results show that the improved version has 23% fewer L2 cache misses.

We do not have sufficiently fine granularity in the performance measurements to document how much of the performance contributions are the result of the improved data copying vs. the improved hextile encoding. We believe that the largest contribution comes from using the Intel SSE2 instructions to improve the data copying.

4.5.2 Using a Multi-thread Architecture

The approach using multi-thread architecture is designed to benefit from multiple CPUs. Multiple CPU has become a new trend of CPU performance, but TightVNC X server is a single thread, which cannot benefit from multiple CPUs. So a Multi-thread architecture and design have to be developed and implemented.

To adapt VNC to a display wall and improve performance, we made several changes, and used the TightVNC implementation of VNC as a starting point for the resulting TiledVNC system. To utilize multi-core architectures, we change the VNC server from being single-threaded to multi-threaded. To control the load on both the server and client side we change the update protocol of the VNC server from a viewer pull to a server push model. The server initially waits until all viewers connect to it, and

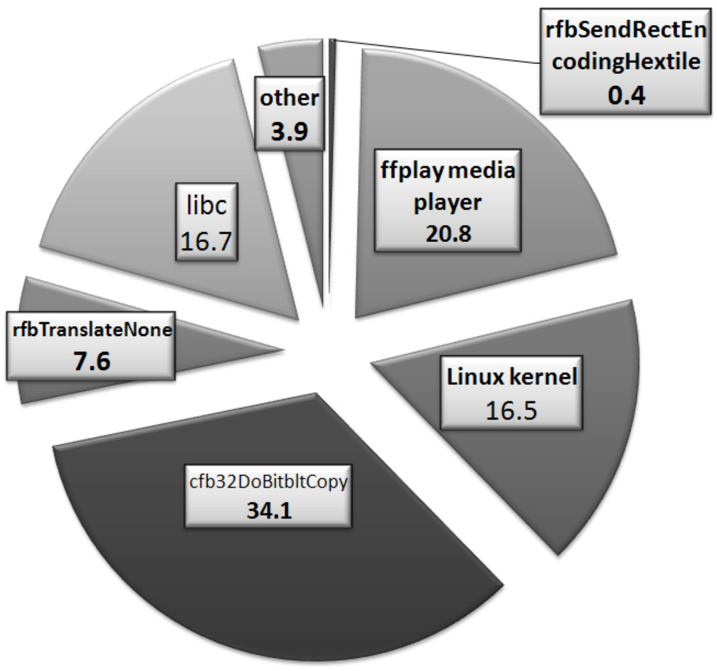


Figure 4.13: Improved VNC L2 Cache Miss

then the server periodically pushes updates to the viewers. To reduce the period when tiles show content from different frames, we only push updates for the same frame to all viewers. This was simplified by the server push model. We also remove the mouse and keyboard input handler from all viewers because in the case of a display wall using VNC all input devices can be connected directly to the VNC server computer instead of to the viewers.

From Single-Threading to Multi-Threading

Figure 4.14 illustrates the architecture of the TiledVNC multi-threaded VNC server. The idea is to have a set of threads waiting on a timer. When a timeout happens, the threads get a task from a pool of tasks. Each task indicates an area of the virtual frame buffer corresponding to a tile of the display wall. A thread scans the frame buffer for dirty regions that needs to be updated, and if there are any, it will compress the data and send it to the corresponding viewer. Then the thread goes to the pool of tasks and gets a new area to check. A counter is used to keep track of the number of remaining tasks. When all tasks are done, the threads block for the next timeout. We implemented the server in C, using the Pthread [11] thread package. We use a Pthread monitor condition variable to have threads wait.

From Viewer Pull to Server Push

We have changed the viewer pull model to a server push model to let the server have better control over its work load and the update rate. The assumption is that the viewers always will have more resources available than they need to display the updates sent from the server.

A VNC server usually uses a viewer pull model. The server waits for requests for updates from the

VNC viewers, and services them as soon as they arrive. If the server finds an update it is sent as soon as possible. This approach lets the viewers request an update only when they are ready, and the server only has to send updates, thereby creating network traffic and using bandwidth, when there are viewers ready to receive. However, by just requesting an update, a viewer forces the server to look for updates and encode them as soon as possible.

If we analyse some interesting permutations of resolution, network bandwidth, and number of viewers we find:

Low desktop resolution, low network bandwidth, few viewers: Even when a high level of compression is used, the low resolution and small number of viewers do not give the server a too high load, and the media player (in our case) gets more CPU resources. The server can keep up with the requests from the viewers. The result is a relatively good frame rate.

High desktop resolution, low network bandwidth, many viewers: A high level of compression is needed, and this together with the high number of viewers gives the server a high load, and the media player gets less CPU resources. The server cannot keep up with the requests from the viewers. The low bandwidth will further delay the receiving of updates. The result is a very low frame rate.

High desktop resolution, high network bandwidth, many viewers: A high level of compression is needed, and this together with the high number of viewers gives the server a high load, and the media player gets less CPU resources. The server cannot keep up with the requests from the viewers. In addition to less requests, the high bandwidth will mean that the network is not the bottleneck, and will not reduce the frame rate further. The result is still a low frame rate.

The viewer pull based VNC model works better for usage domains with a standard sized PC desktop with just one or a few viewers than it does for a high-resolution display wall desktop with potentially many more viewers. A high-resolution VNC server with multiple clients spends more time on encoding pixels than transferring the pixels over the network. The many viewers also force the server to service them as soon as possible. Consequently, the server has little influence over its own work load. The performance of the VNC server is impacted by the frequency of updates.

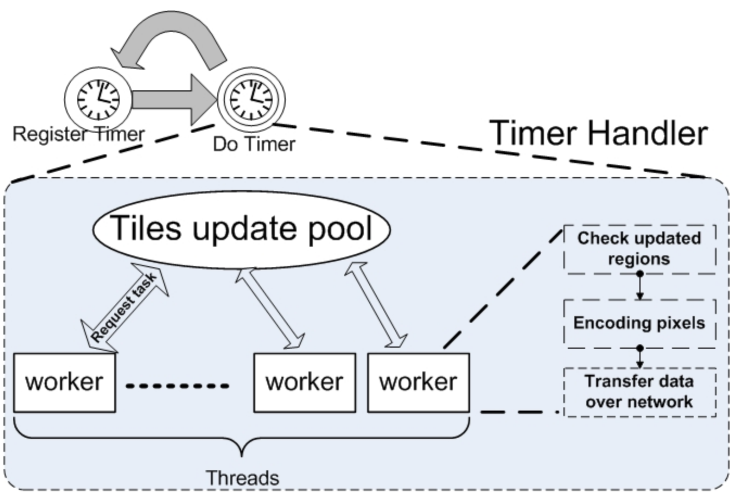


Figure 4.14: Multi-thread Display Wall Desktop

Figure 4.15 describes time distribution during two contiguous frame updates. The time ΔT between two contiguous updates is the sum of T_x, $T_{transfer}$ and T_{delay}, as shown in Figure 4.15.

T_x and $T_{transfer}$ are insignificant for the standard PC desktop resolution case. When the size of the desktop increases, T_x and $T_{transfer}$ grow larger. T_x in particular can become large in the high resolution. T_{delay} is the duration between updates. During this time the media player application may also get more CPU resources because the server may wait idle for new viewer requests or for the timeout. Reducing the update frequency will reduce the server load. This can be achieved by increasing T_{delay}.

Consistency between Tiles

The viewer pulls update protocol used by VNC, when used in a tiled display wall, resulting in the possibility of viewers displaying content from different frames. This is because each viewer requests and gets updates independently of each other. The server push update protocol makes it simple to reduce the period when tiles show content from different frames by simply pushing updates from the same frame to all viewers before the next frame is pushed out. Even if viewers receive the updates at slightly different times, the updates are from the same frame. This works well as long as the viewers have sufficient resources to receive and display all updates. This is a realistic assumption for a display wall with many viewers and a heavily loaded server.

Experimental Design

The period between timeouts, the delay, lets the server control its load and impact the performance. Different numbers of threads can be used. We used a computer with a 3.8 GHz Intel(R) Xeon(TM) CPU and 8 G RAM memory to run a TiledVNC server. The operating system is 64-bit Redhat Linux RHEL 5. The TiledVNC server is configured to use four threads to handle updates. FPS, UFP and time are evaluated by playing videos.

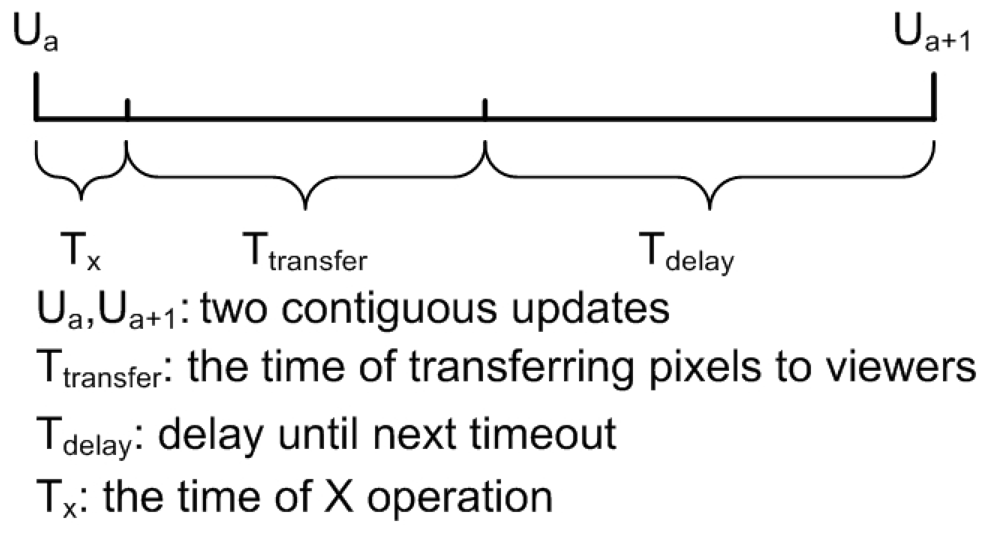

U_a
U_{a+1}
T_x
$T_{transfer}$
T_{delay}
U_a, U_{a+1}: two contiguous updates
$T_{transfer}$: the time of transferring pixels to viewers
T_{delay}: delay until next timeout
T_x: the time of X operation

Figure 4.15: Time Distribution

Experimental Results and Discussion

The results from the experiments are shown in Figures 4.16, 4.17 and 4.18. TiledVNC in the figures is an implementation of multi-thread architecture. The X-axis is the delay between timeouts, T_{delay} in milliseconds. The Y-axis is the frame rate (FPS) or the percentage of updated frames (UFP).

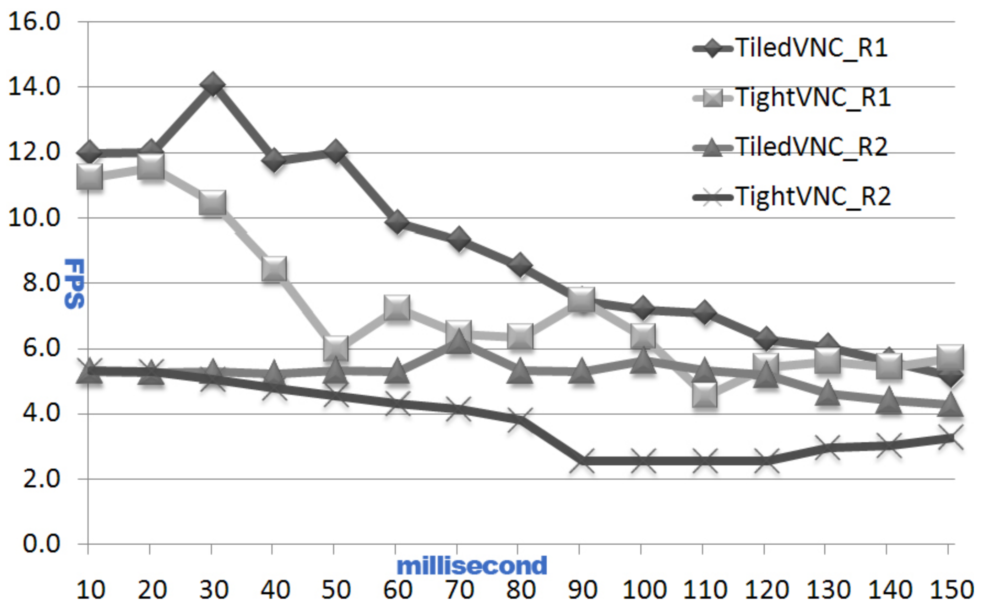


Figure 4.16: FPS at the Display Wall

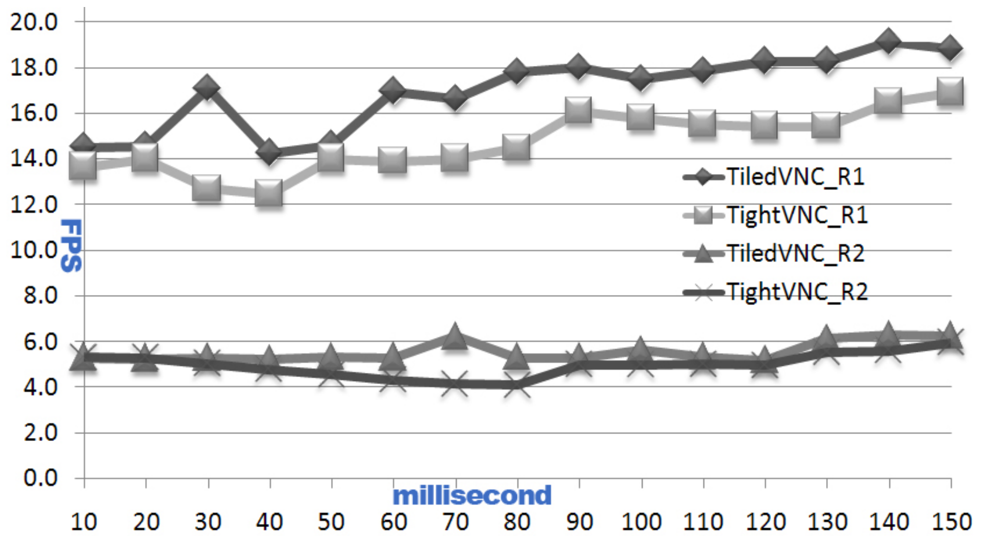


Figure 4.17: FPS at the VNC Server

The results show that the best frame rate as seen by the **viewers** for the 3 mega-pixels video was achieved when updates were done every 30ms. In this case TiledVNC increased the frame rate to 14 FPS, or about 34% more than TightVNC. About 80% of the updates done at the server side were displayed on the display wall.

The best frame rate as seen by the viewers for the 6.75 mega-pixels video was achieved when updates

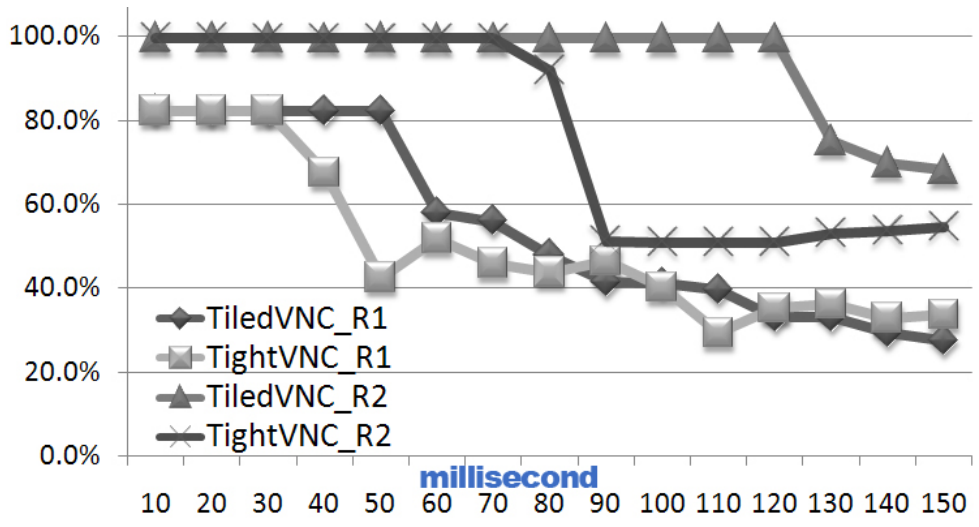


Figure 4.18: UFP

T_{delay}	30 ms	70 ms
TiledVNC_R1	211	216
TiledVNC_R2	679	579
TightVNC_R1	283	257
TightVNC_R2	712	869

Table 4.3: Time to Play Back a 120 Seconds Long Video

were done more rarely, at 70ms. In this case TiledVNC increased the frame rate to 6 FPS, or about 46% more than TightVNC. About 100% of the updates done at the server side were displayed on the display wall.

TiledVNC is performing better than TightVNC in all cases, but when the delay between updates increases, the frame rate decreases for both systems to between 3-6 FPS.

The results show that the best frame rate at the **server** for the 3 mega-pixels video was achieved when updates were done every 140ms. In this case TiledVNC achieved a frame rate of 19 FPS, about 15% better than TightVNC.

The best frame rate at the server for the 6.75 mega-pixels video was achieved when updates were done at 70 ms and greater than 130 ms. In this case TiledVNC increased the frame rate to about 6 FPS, but this is only slightly better than TightVNC.

TiledVNC performs better than TightVNC in all cases. At the server, when the delay between updates increases, the frame rate increases for both systems when playing the R1 video from about 14-15 to 17-19 FPS. However, for the R2 video, the frame rate stays at around 5-6 FPS almost independently of delay time. Playing back R2 and running the server seems to saturate the computer used. In this case a faster computer should give better performance.

From Figure 4.18, it can be seen that TightVNC begins to skip frames earlier than TiledVNC. This is because TightVNC uses a single core, while TiledVNC benefits from using all four cores. However, both systems have the same UFP at delays below 30 and 70 ms respectively for R1 and R2.

In practical terms, a user viewing the videos on a display wall will experience that the 120 seconds long videos takes longer to play back. TightVNC needs 257 and 712 seconds to play back R1 and R2 for the best cases, respectively, to play back R1 and R2. For TiledVNC the videos take 211 and 579 seconds for the best cases to play back.

Comparing the results for TightVNC in Table 4.3 with Table 4.1, the performance is improved because of the more powerful computer used in the last set of experiments, and because using 30 ms or 70 ms gives better performance than the default 40ms used in the first set of experiments.

4.5.3 The Improvement Using GPUs of TightVNC

The approach using GPUs is designed to benefit from many-core GPUs, because GPU has changed from a special purpose graphical hardware to a general-purpose computing device. This approach will change TightVNC to let a GPU to handle pixel copy and pixel compression.

Reasons for Using CUDA and Challenges

CUDA (Compute Unified Device Architecture) is a parallel computing architecture, which uses NVIDIA GPUs. CUDA provides a software environment to use C as the development language, which is easy to use together with a display wall desktop. The idea behind CUDA is that GPU is specialized for computing-intensive, highly parallel computations. CUDA is well-suited to address problems that can

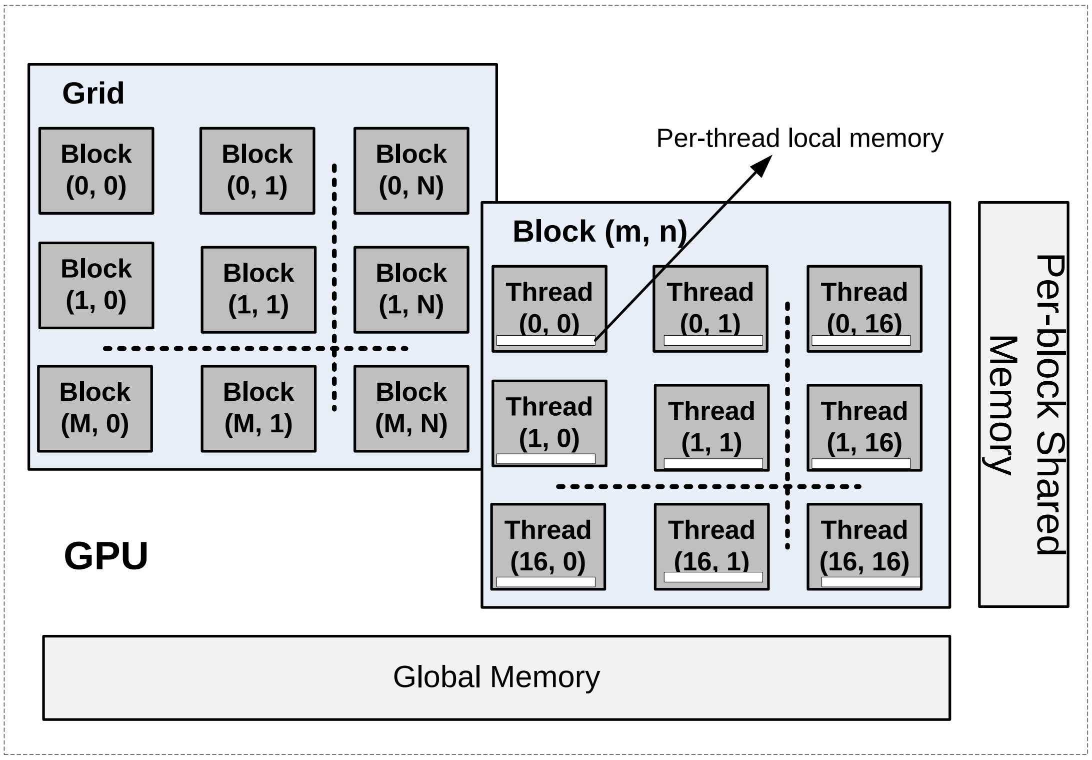


Figure 4.19: CUDA Thread Batching

be expressed as data-parallel computations. The display wall desktop is highly computing-intensive and data-parallel, which is expected to benefit from GPU.

GPU is viewed as a computing device in CUDA, which is able to execute a very high number of threads in parallel. Kernels, which are data-parallel computing-intensive portions of applications running on the host, are off-loaded onto the device. Those kernels are executed many times and independently on different data. They can be isolated into a function that is executed on the device as many different threads. Pixel bitblt is to handle each pixel independently so that it is typically data-parallel. Pixel encoding is also to compress independent pixel regions.

There are two separate memory spaces in host and GPU: host memory and device memory. CUDA applications have an execution pattern: data are copied from host to device before CUDA computing, and data are copied back to host after CUDA computing. Large data copying at the display wall desktop will have a heavy impact on the performance. The challenge is to decrease the number of times the memory is copied between the host and GPU. Pixel comparison is another challenge for performance.

Figure 4.19 demonstrates the data model with CUDA, where a thread block is a batch of threads that work on one pixels region at the display wall desktop. Each thread has a private local memory. All threads have access to the same global memory. Global memory and local memory are not cached in CUDA. Access to them is expensive. CUDA provides shared memory as fast as registers to make threads cooperate and share data efficiently in one block. It also supports synchronizing their execution to coordinate memory access.

Pixel Bitblt Using CUDA

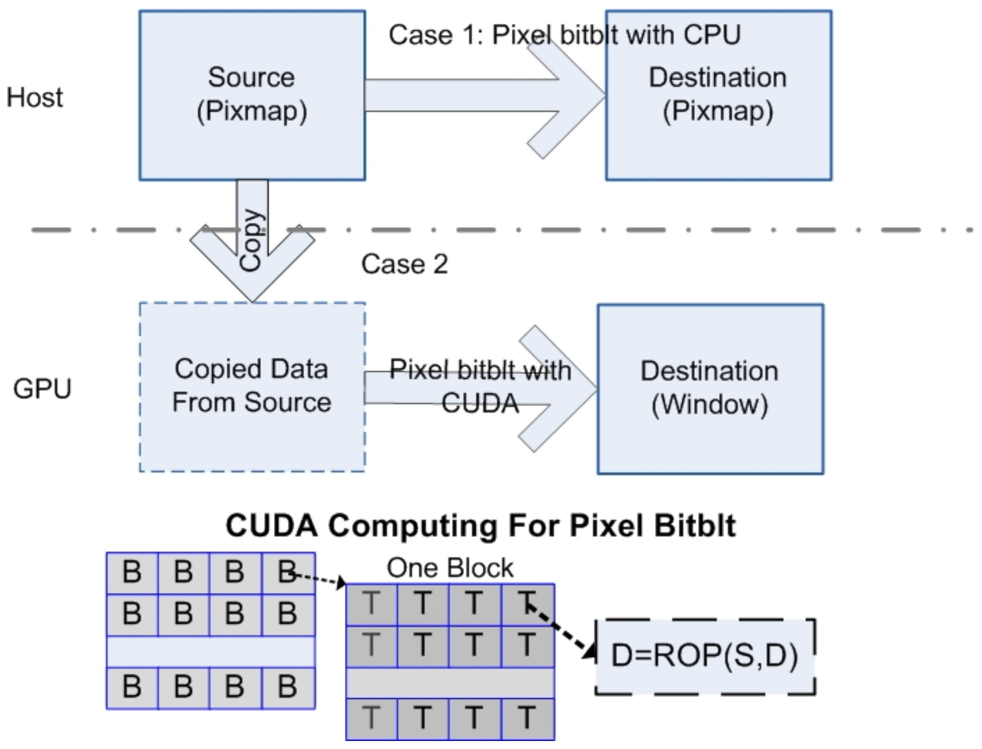


Figure 4.20: Pixel Bitblt with CUDA in gTiledVNC

In order to decrease the number of times the memory is copied, VFB of X VNC server is put into global memory in the GPU device's memory. CUDA 2.2 supports zero-copy buffer on integrated GPUs, where the CPU and GPU memory are physically the same and the buffers in the host can be mapped into the CUDA address space. VFB uses zero-copy buffer in order to avoid the overhead of memory copy between host and GPU. Zero-copy buffer makes CPU and GPU work seamlessly.

X server uses a drawable as a descriptor of a surface that graphics are drawn into. X server supports two types of drawables, either a window on the screen or a pixmap in memory. Pixmap is an off-screen graphic area in host memory. Window is an area on the screen that can be drawn into by graphic routines. VFB is used as the screen in X VNC server. As a result, window is referred directly to VFB in the display wall desktop. All graphic operations work on drawables, and operations are available to copy patches from one drawable to another. All operations related to window will be handled with GPU.

Graphic routines are divided into four cases. When both the source and destination drawables are pixmaps, CPU will do with pixel bitblt. The other cases will be done with CUDA. Figure 4.20 describes two cases. Case 1 is pixel bitblt using CPU when the source and destination are pixmaps. When one of the drawables is pixmap, the data of pixmap are copied to the GPU before CUDA computing. There is no memory copy when both drawables are windows. Case 2 is pixel bitblt using GPU when the source is in main memory and the destination is in GPU memory.

CUDA supports that the maximum number of threads per block is 512. Because ROP on pixels is independent of each other in pixel bitblt, it is easy to do with one operation on one pixel in one thread, shown in Figure 4.20. When both the source and destination of bitblt are windows, it will theoretically speed up 512 times, because of the 512 pixels each time, as shown in Figure 4.20. The typical case is putimage, where the source is a pixmap and the destination is a window. In that case, there is one memory copying between the host memory and the device memory.

Hextile Encoding Using CUDA

Hextile is relatively fast compared with other pixel encoding methods at the display wall. There are the following steps in hextile encoding: (1) In order to improve the compression ratio, the background and foreground pixels are selected first in each 16x16 tile; (2) The sub-rectangles are looked for in one tile, which are the same colours and not the background pixel; (3) When a sub-rectangle is found, pixels are encoded and the sub-rectangle is filled with the background pixel. If the length of final encoded data is more than the length of raw data, raw encoding will be used. Although hextile is an efficient pixel compression, the time complexity is very high when CPU is used to implement it in the high resolution case.

Hextile encoding of TightVNC is re-implemented using CUDA. This method is that one grid handles hextile encoding and each thread is to finish encoding pixels in one 16x16 tile. Figure 4.21 demonstrates hextile encoding with CUDA. Each thread chooses background (bg) color and foreground (fg) color, and finds and encodes some sub-rectangles where pixel's color is same. After each thread has done hextile encoding, synchronization has to be used to wait for all threads finishing pixel encoding. The reason is that the length of compressed data in one tile is not fixed. The position of each tile in the data buffer cannot be calculated until all information of the lengths is collected. After each thread gets its position in the data buffer, the encoded data can be written into the data buffer.

The challenge is that all of doing this is involved in a lot of pixel comparison and memory copies. Those operations have an impact on the performance of CUDA. The background pixel can efficiently increase the compression ratio.

Experimental Design

gTiledVNC has been implemented based on TightVNC, where the codes include a CUDA interface library and some modifications for window bitblt and hextile encoding. The display wall computers run 32-bit Rocks 4.1 Linux on a cluster of Dell Precision WS 370s, each with 2GB RAM and a 3.2 GHz Intel P4 Prescott CPU. The server node has 2.5GB RAM, 3.2 GHz CPU, and one integrated GeForce GTX 295. That node runs 64-bit Ubuntu 9.04 and installs CUDA 2.2. We use one video, which is 3 mega-pixels each frame, 30 FPS, 3000-frame, and MPEG4 encoding to emulate updates to a high-resolution desktop. The video plays with ffplay [18] on the server. It plays back on the display wall with vncviewer.

A	CPU with VFB in host
B	CPU with VFB in GPU
C	Bitblt using GPU
D	Encoding using GPU
E	Bitblt and encoding using GPU

Table 4.4: Experimental Configuration in gTiledVNC

Table 4.4 describes the experimental configuration in gTiledVNC. Case A is using CPU-only with VFB in host. VFB uses zero-copy buffer in the other cases. Case B is when VFB uses zero-copy buffer and

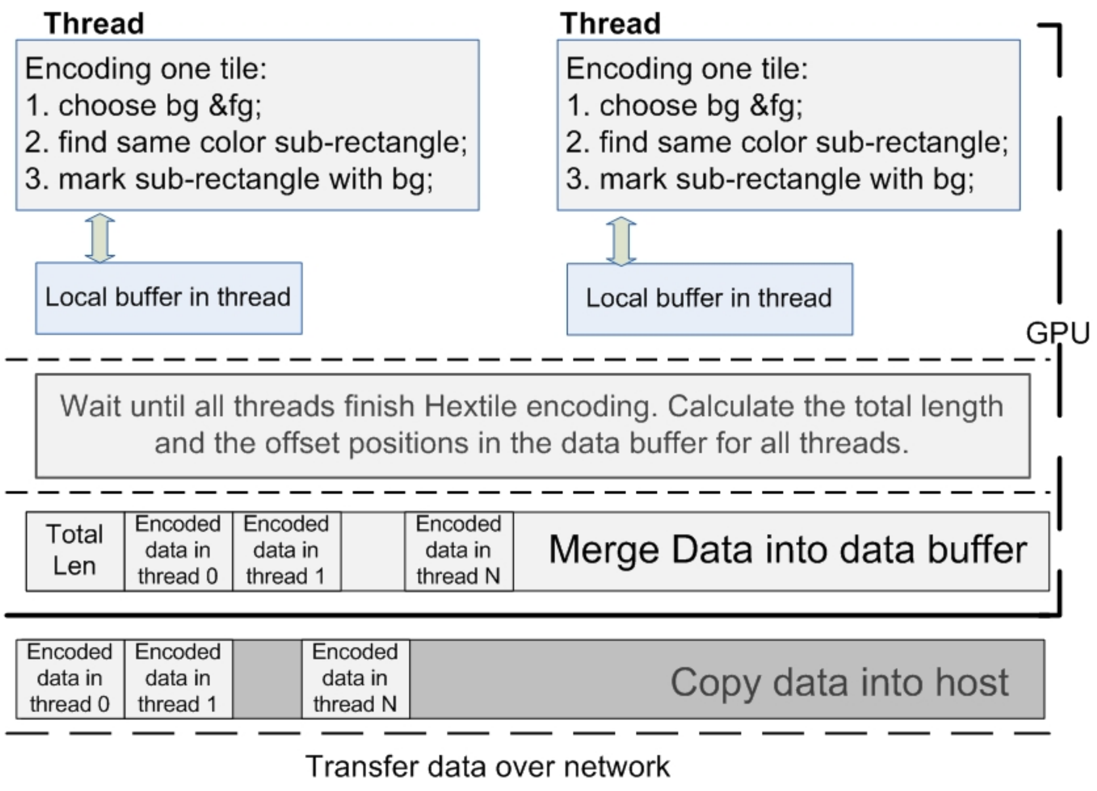

Thread
Encoding one tile:
1. choose bg &fg;
2. find same color sub-rectangle;
3. mark sub-rectangle with bg;
Local buffer in thread
Thread
Encoding one tile:
1. choose bg &fg;
2. find same color sub-rectangle;
3. mark sub-rectangle with bg;
Local buffer in thread
GPU
Wait until all threads finish Hextile encoding. Calculate the total length and the offset positions in the data buffer for all threads.
Total Len
Encoded data in thread 0
Encoded data in thread 1
Encoded data in thread N
Merge Data into data buffer
Encoded data in thread 0
Encoded data in thread 1
Encoded data in thread N
Copy data into host
Transfer data over network

Figure 4.21: Hextile Encoding Each Block in gTiledVNC

CPU does all computation. Case C only uses GPU to do bitblt. Case D only uses GPU to do hextile encoding. Case E uses GPU to do bitblt and hextile, where each block has 15 threads and one tile is copied into shared memory first.

Experimental Results and Discussion

The result is shown in Figure 4.22. FPS on the Y-axis is the number of frames per second seen in front of the display wall. The X-axis represents different cases using GPU. FPS of A and B is same, which is 9.9. FPS of E decreases to 1.8.

FPS of A and B is same. It shows that VFB using zero-copy buffer has no impact on FPS. Hextile encoding using GPU is mainly a bottleneck because FPS of D is almost the same as FPS of E.

4.6 Discussion

Two videos at 3 and 6.75 mega pixels were used in the experiments. While these videos played back on all the computers we had available, a 22 mega-pixel video did not, making it impractical to use it in the experiments. However, the lower resolution videos do reflect interesting collaboration settings where full desktop updates are rare. One such setting is collaboration using many static documents and a few videos and web sites with animations.

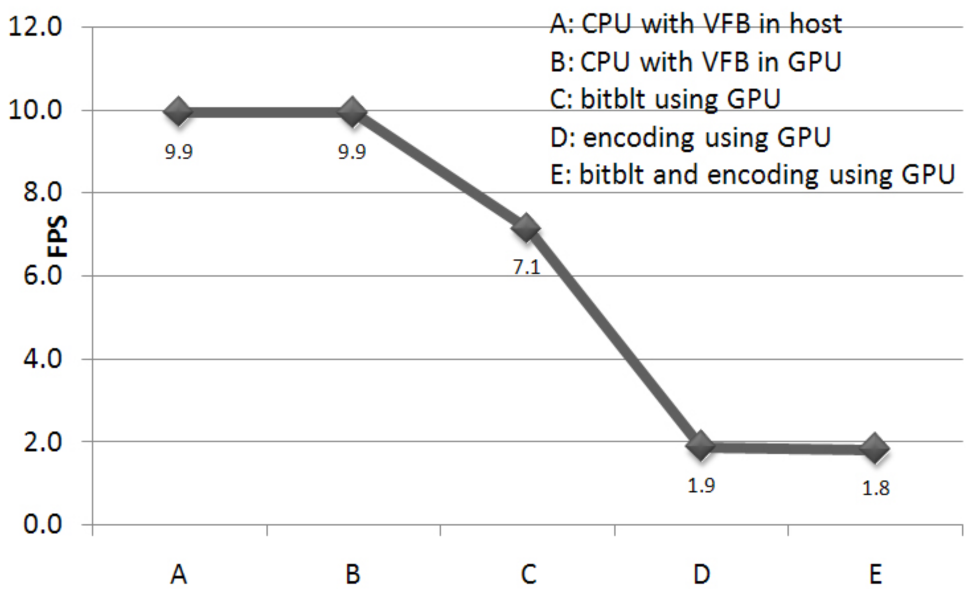


Figure 4.22: Performance of Display Wall Desktop Using GPU

There are two characteristics behind the implementation of a display wall desktop. One is that VFB resides in the main memory and resolution at the display wall desktop is very high. This results in that memory operations are CPU-consuming. Another is pixel comparison. Because of high resolution, pixel comparison is also CPU-consuming. Pixel compression is used to reduce the requirement of network bandwidth.

The size of each frame of a 22 mega pixel desktop at 32-bit colour depth is 84MB, or about 0.6 Gbits. For the 3 and 6.75 mega-pixel videos the size of each frame is, respectively, 12 MB and 28 MB. The 1 Gbit Ethernet we are using can sustain an end-to-end bandwidth of about, or less than, 0.8 Gbit/sec, resulting in only 1-2 FPS when updating all the pixels of a 22 mega-pixel desktop without using compression on the pixel data. To update all the pixels at 25 FPS without using compression, we must send at about 2 GB/sec, or 16 Gbits/sec. The gigabit Ethernet has about 20 times less bandwidth than is needed to do this. Even for the 3 and 6.75 mega-pixels videos the Gigabit Ethernet has too low bandwidth to sustain 25 FPS when using raw pixel data. Consequently, either a much faster network is needed, or pixel data compression must be used in order to at least reduce the network bottleneck and achieve better frame rates. Faster networks are available, but are not yet commodified and are therefore still expensive. If compression is used, it must be done using CPU and memory because the VNC server does not use the graphics processing unit (GPU). For dynamic documents, like a video, compression puts a heavy load on the CPU and the compression ratio may still not be very good. For more static documents, like PDF documents and web pages, the CPU load will also be high, but at least the compression ratio becomes good cutting down on network traffic.

The improvements at the instruction level to TightVNC were focused on improving the data copying using the Intel SSE2 instruction set, and improving the hextile encoding. Of the techniques applied, the improved data copying can be used in other data copying intensive applications. Cache fetch is helpful for memory movement. The hextile encoding has a more limited usage but can be applied in other display related systems. However, the total improvements of performance are limited because SSE2 has a 128-bit memory bus and there is four times speedup in the best case.

The single computer running the VNC server and the applications does not have the resources to compress and transmit a high-resolution desktop at more than a single digit frame rate. In a collaborative setting the performance can be acceptable or not depending on how the display wall is used. If it is used to view a set of static documents with little or light scrolling through the documents, the performance using VNC is in our experience not an obstacle to the work flow. This is also the case when, say, a paper is done collaboratively on a display wall. In this case a typical setup is to have open 3-10 editor windows, the PDF version of the paper, and all the figures and tables in separate windows. The large size and resolution of a display wall implies that many documents or many pages of a few documents can be displayed all at the same time thereby reducing the need for updates. When dynamic documents are used, like scrolling through complex documents and images, playing videos, running simulations and doing visualizations of large scientific data sets, using VNC will in our experience result in frame rates and application performance low enough to frustrate the users and reduce the effectiveness of the collaboration. Our measurements support our subjective experiences.

In comparison with the instruction level and GPU, multi-thread architecture (TiledVNC) leads to better performance. FPS of TiledVNC has 34% more than FPS of TightVNC. Although the performance of TiledVNC is better than TightVNC, it still suffers from low FPS. One main reason is that updating the virtual frame buffer has no hardware (GPU) support. However, we still benefit from multiple cores. The compression rate of the hextile encoding used by TightVNC and TiledVNC is about 5. When $T_{delay} = 30ms$, TiledVNC sends about $34\ MB/sec$ and $29\ MB/sec$ into the network when playing back the 3 and 6.75 mega-pixels videos, respectively. The gigabit Ethernet can support about $100\ MB/sec$. With more cores the multi-threaded TiledVNC should be able to push more updates into the network. For the 3-megapixel video, we estimate that using eight cores may give us about 19 FPS. This is about $45\ MB/sec$, and still less than what a gigabit Ethernet will support. This is interesting because it indicates that there are performance benefits for TiledVNC to be expected from more cores, and it is simpler to update to a computer with more cores than to update the whole network.

The performance of using GPUs is much lower than 15 FPS using multi-CPUs. There are 480 processors in GeForce GTX 295, but FPS does not vary with an increasing number of threads per block. It cannot utilize the capacity of GPU efficiently when the code is ported directly from CPU to GPU, where one thread does hextile encoding for one tile. One block works together to implement hextile encoding for one tile in the future, where many threads can speedup hextile encoding. One block for one tile can also utilize shared memory to improve the performance.

CUDA has two distinct memory spaces. One is on the GPU, and another is on the main memory of the host. It interchanges data by coping data between CPU and GPU. However, high resolution desktop means a great number of pixel copies between CPU and GPU, which leads to the big overhead. CUDA supports zero-copy mode in integrated GPUs. When zero-copy buffer is used as VFB, the overhead is little compared with the buffer in the host, according to the experimental results. The advantage is that zero-copy buffer implements data interchange without buffer copies. The disadvantage is that it depends on integrated GPUs and consumes the memory in host.

Hextile encoding using CUDA has a large negative impact on performance. The reasons are that GPU is not good to do a lot of pixel comparison and memory operations. An amount of pixel comparison leads to heavy performance penalty on the GPU. When each thread does hextile encoding for one tile, encoding is in need of memory buffer. Each thread consumes 1KB buffer to copy pixels in one tile. The performance of using shared memory is better than that of using local memory, because shared memory is as fast as the registers. However, it supports 16KB for one block. As a result, the number of threads per block is only up to 15 when shared memory is used for hextile encoding.

4.7 Conclusion

This chapter describes the architecture of high resolution display wall desktops, using X server and VNC protocol. This architecture can provide high resolution and remain compatible with existing applications. By profiling desktops, it is found that it is CPU-intensive, and two main bottlenecks are data movement and pixel encoding. As a result, performance improvements have to be applied. Three improvements are implemented in this chapter, including using instruction level, multi-CPUs, and GPUs. According to experimental results, multi-thread architecture gains the best improvement.

Chapter 5

Discussion

5.1 Background

We argue that a pixel level model is well-suited to share display content at low resolution and high resolution. However, this model also introduces some performance problems, such as high CPU and network usage. In particular, it is more CPU- and network- intensive when display content is shared at high resolution, even if we have already applied three improvement approaches to high resolution display wall desktops. These approaches are: using SIMD instructions, using a multi-thread architecture and using many-core GPUs. The best improvement is to use a multi-thread architecture, which is up to about 14 FPS at 3 mega-pixels per frame. When the size per frame increases to 6.75 mega-pixels, the best FPS is about 6. It shows that FPS decreases heavily when the resolution increases.

In order to demonstrate this FPS problem, the data path for sharing display content from a server to a viewer is shown in Figure 5.1. Data path includes a lot of memory copies and transmission of network packets. A server reads back pixels from a virtual frame buffer and encodes those pixels. This work is done by the CPU and memory systems. The encoded data are sent via network cards. CPUs usually access network cards via a PCI interface. According to this data path from CPU to network, sharing display content depends on CPU devices, memory devices, PCI devices and Ethernet devices in current computer systems. It is known from the data path that the performance of sharing display content has to be subject to the minimum bandwidth of those devices.

The bandwidth of devices, which are used by personal computers, is shown in Table 5.1. The bandwidth number is peak transfer rate in the table. The DDR peak transfer rate is obtained by *memory clock rate * bus clock multiplier * data rate * number of bits transferred / number of bits per byte*. For example, the memory clock rate of DDR3-1600 is 200 MHz. If data are transferred 64 bits at a time, the peak transfer rate of DDR3-1600 is $200 \times 4 \times 2 \times 64/8 = 12800$ MB/s. The peak rate of Ethernet devices are calculated by max transfer rate / number of bits per byte.

The peak bandwidth of CPU is related with CPU frequency. However, CPU frequency is less than 4 GHz from Chapter 1. If we assume that read and write operations can be done in one cycle, then the peak read or write bandwidth of 4 GHz CPU is 32 GB/s when data are transferred 64 bits at a time. In fact, the real bandwidth of read or write operations are much less than this number. One of the reasons is that read and write operations cannot be done in one cycle.

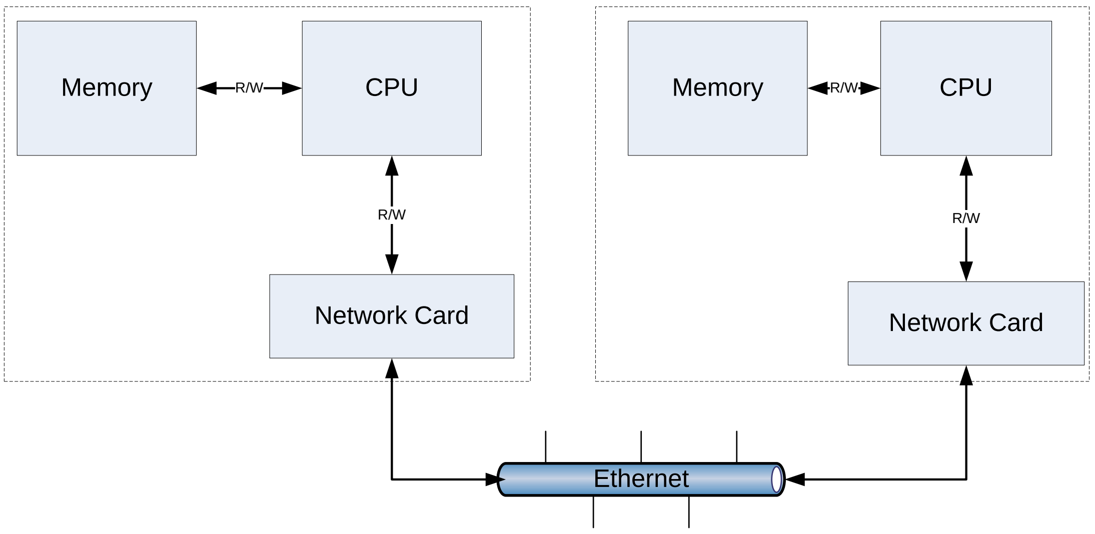


Figure 5.1: Data Path of Sharing Display Content

Device	Type	Peak Transfer Rate (MB/s)
Memory	DDR3-1600	12800
Memory	DDR2-533	4266
Network	Fast Ethernet	12.5
Network	Gigabit Ethernet	125

Table 5.1: Bandwidth of Devices

Because there is a lot of data movement during sharing of the display content, the cost of memory copy is used to evaluate the performance of memory and CPU systems. In order to give an example, an actual platform, rockslcd, is used to get real performance information. Rockslcd has 64-bit 3.2 GHz CPU, 2.5 GB DDR2-533 memory. Table 5.2 gives memory bandwidth data, which are the result of lmbench3 [56] at rockslcd. The bandwidth of memory read is 4715 MB/s, and the bandwidth of memory write is 2000 MB/s. Libc copy contains a read operation and a write operation at a time. The bandwidth of Libc copy is 1470 MB/s, which is 34.5% of DDR2-533's peak transfer rate.

From Table 5.2, the cycles for one memory copy (C) can be estimated.

$$\frac{3.2 \times 64/8}{C} = \frac{1470}{1024} \Rightarrow C \approx 18$$

This means that CPU cycles for one memory copy are about 18. This number will be used for the following discussion.

This chapter will discuss what kind of hardware can satisfy the requirement to support one or many viewers receiving display content at 25 FPS. Users will not be aware of the latency of visualization at 25 FPS. However, it is still difficult to reach the target, 25 FPS at the viewers. So it is necessary to answer the following questions:

Memory Operation	Memory Read	Memory Write	Libc Copy
Bandwidth(MB/s)	4715	2000	1470

Table 5.2: Memory Bandwidth at Rockslcd

- Is it possible to achieve our target which is to drive a viewer or a display wall at 25 FPS?
- Do we only need to wait for better hardware to meet the requirement?
- Do we have to improve the software even if we have better hardware?

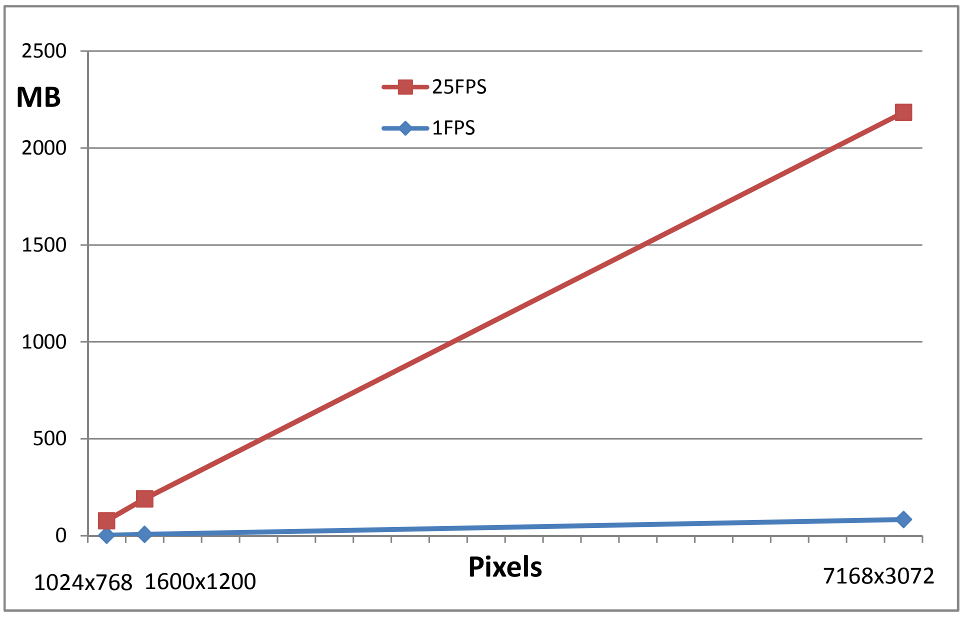


Figure 5.2: The Relationship between Pixels and Data Size

In order to answer the above questions, a model is needed to evaluate the performance of sharing display content. To simplify the discussion, it is assumed specifically that the size of each frame at viewers is 1600×1200, which is usually supported by personal computers now. The targeted FPS is 25 at viewers. Each pixel is represented with 32-bit (4 bytes). So the data size of one frame $Ndataperframe$ is:

$$Ndataperframe = \frac{1600 \times 1200 \times 4}{1024 \times 1024} \approx 7.3\ MB$$

The total size of 25 frames ($Ndata$) per second is:

$$Ndata = Ndataperframe \times 25 \approx 183.1\ MB$$

That means that the server must be able to transmit data to each viewer at 183.1 MB per second in order to reach 25 FPS.

In order to show the relationship between different resolutions and data, Figure 5.2 is given, which gives three different resolutions $(1024 \times 768, 1600 \times 1200, 7168 \times 3072)$ at 1 FPS and 25 FPS. From this figure, we know that the data to handle increases when the resolution goes up. When FPS increases, the data to handle increases.

In the discussion, 28 viewers are used to represent ”many viewers” for simplification of the discussion. The reason for this decision is that we have already an experimental platform, a 28-node display wall cluster. That number is equal to the number of the nodes in the display wall cluster. This makes the discussion controllable. So when the number of viewers is up to 28 at 25 FPS on the server, the bandwidth required is as follows: $Ndata \times 28 = 183.1 \times 28 = 5126.8\ MB/s$.

The performance of sharing display content is subject to Moore's Law and Amdahl's Law. Although Moore's Law states that the density of transistors on a chip will double every 18 months, the clock speeds haven't increased at the same speed because of thermal issues. As a result, one single core will be the bottleneck of the whole system. Multi-core CPUs are an option. However, applications cannot benefit from multi-core CPUs directly. Parallel programming must be used for better performance. So the effect of multi-core CPUs will be discussed.

5.2 Model for Sharing Display Content

Figure 5.3 describes how display content is shared to one viewer. Applications are not included in this figure in order to simplify the description of sharing display content. This figure describes the minimum steps needed to share display content. In fact, the real data path is more complex and longer from user space to Ethernet in modern operating systems. The first step is to copy the content of VFB to a local in-memory buffer, and the final step is to copy the content to a network buffer for transmission to viewers over networks. So pixels undergo at least two copies. Pixel compression before transmission is optional. Whether pixel compression is used depends on the specific hardware environment. For example, it is usually without pixel compression when the server and viewers run in the same node. However, if a viewer accesses the server via a wireless network, a pixel compression has to be used for better FPS. Compression is to decrease the requirement of network bandwidth.

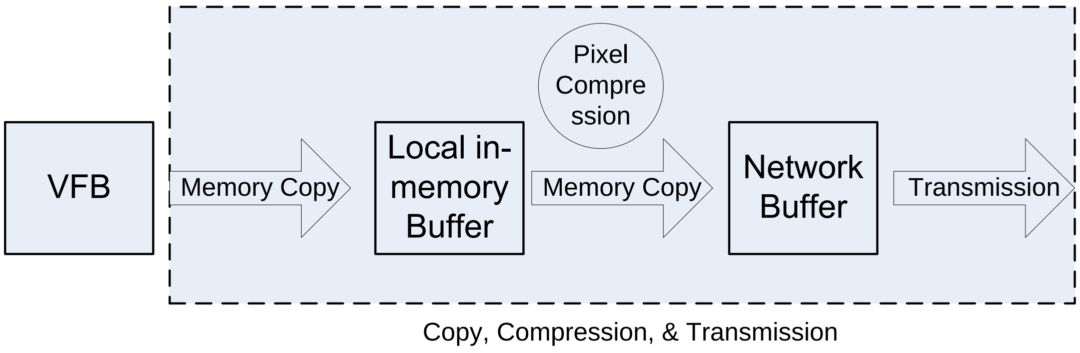


Figure 5.3: Sharing Display Content for One Viewer

When Figure 5.3 is extended to multiple viewers, there are two following models, VNC model and MultiStream model. VNC model is illustrated in Figure 5.4, which is a centralized, pull-model, non-distributed architecture. In VNC model, copy, compression and transmission will be done in one server node. However, MultiStream model is a little different in Figure 5.5, where the display content is sent to another server node which is responsible for the distribution of the display content to viewers. As a result, VNC model is simple in comparison with MultiStream model. However, MultiStream model is more scalable. These two models will be applied in the discussion.

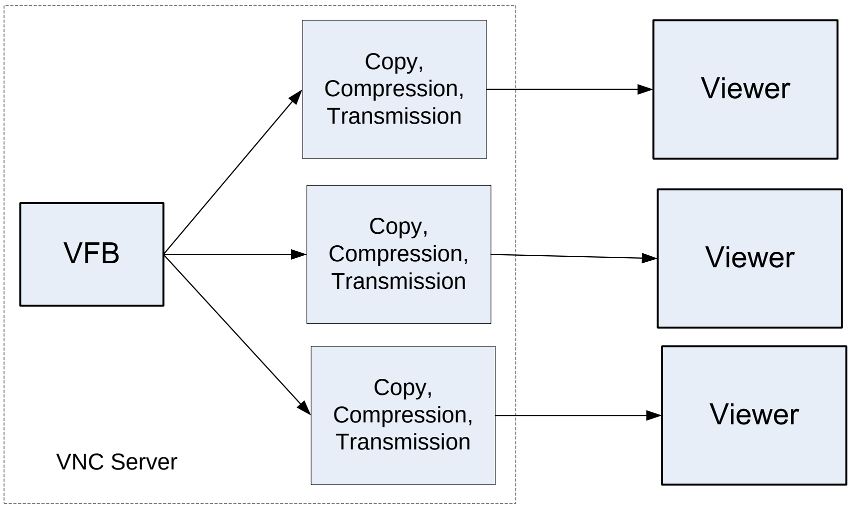

VFB
Copy, Compression, Transmission
Copy, Compression, Transmission
Copy, Compression, Transmission
Viewer
Viewer
Viewer
VNC Server

Figure 5.4: VNC Model for Multiple Viewers

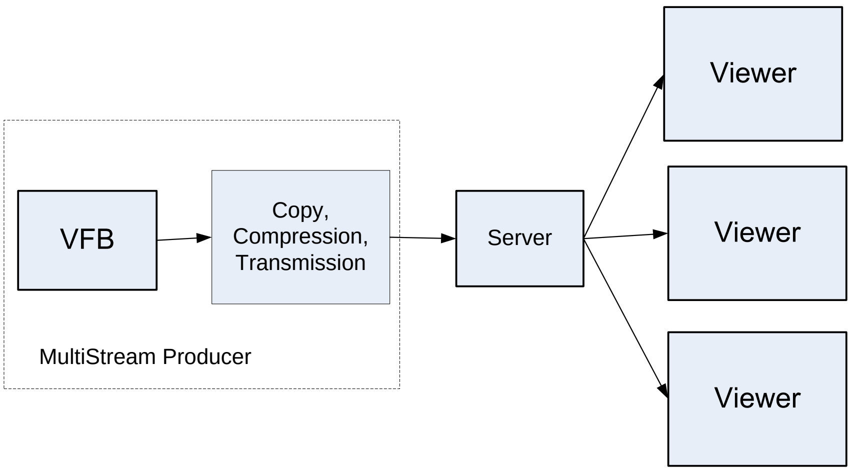


Figure 5.5: MultiStream Model for Multiple Viewers

5.3 Sharing Display Content without Compression

5.3.1 Evaluation Equation for CPU and Network

In order to reach 25 FPS at one viewer, the time (T) which is spent to send 25 frames from the server to a viewer must be less than 1 second. So the following equation is obtained.

$$T = \frac{Ndata}{Bwnetwork} + 2(\frac{Ndata}{Bwmemcpy}) \leq 1$$

Where $Bwnetwork$ stands for bandwidth of network and $Bwmemcpy$ stands for bandwidth of memory copy. Memory is copied at least twice according to Figure 5.3, including copying the content of VFB to local buffers for encoding and copying the encoded data for network transmission.

When the number of viewers ($Nviewer$) increases in VNC model, $T \leq \frac{1}{Nviewer}$. This shows that the

Network Type	Fast Ethernet	Giga Ethernet	10 GbE	100 GbE
Bandwidth	100 Mb/s	1 Gb/s	10 Gb/s	100 Gb/s
Initial standard	1995	1998	2002	2010
Widely Used	2000	2009	N/A	N/A

Table 5.3: Increasing Trend of Ethernet Network Speed

number of viewer connections will impact a VNC server in a VNC model in order to keep 25 FPS. When the number increases, the VNC server has to transfer frames faster. However, the condition is still $T \leq 1$ in MultiStream model.

5.3.2 Discussion

1. $Bwmemcpy \to \infty$

   This assumption is that the capability of CPU and memory systems is infinite. Namely, the time for reading and encoding pixels is close to 0. $Ndata = 183.1\ MB$ is used in the following discussion.

$$T = \frac{Ndata}{Bwnetwork} + 2(\frac{Ndata}{Bwmemcpy}) = \frac{183.1}{Bwnetwork} + 2(\frac{183.1}{\infty}) \leq 1$$
$$\Rightarrow Bwnetwork \geq 183.1\ MB/s = 1464.8\ Mbit/s = 1.4\ Gbit/s$$

   This means that bandwidth of the network must be more than $1.4\ Gbit/s$ if 25 FPS is to be achieved on one viewer when infinite CPU and memory resources are available. The bandwidth is more than the max bandwidth of 1 Giga Ethernet. So 1 Giga Ethernet cannot support 25 FPS at one viewer. When the number of viewers is up to 28, the bandwidth must be $41014.4\ Mbits/s = 40.1\ Gbit/s$.

   Table 5.3 shows the increasing trend of Ethernet network speed. 100 GbE is still in development, which can support the $40\ Gb/s$ that we need. But it is not used yet.

2. $Bwnetwork \to \infty$

   This assumption is that the capability of network is infinite. Namely, the time for transferring encoded pixels trends to 0.

$$T = \frac{Ndata}{Bwnetwork} + 2(\frac{Ndata}{Bwmemcpy}) = \frac{Ndata}{\infty} + 2(\frac{183.1}{Bwmemcpy}) \leq 1$$
$$\Rightarrow Bwmemcpy \geq 366.2\ MB/s = 0.358\ GB/s = 2.86\ Gbit/s$$

   This means that the memory system can sustain one viewer at 25 FPS when the bandwidth of the network is infinite. For example, bandwidth of memory copy is $1470\ MB/s$ ($11.48\ Gbit/s$) at rockslcd, which can satisfy the requirement of one viewer. And rockslcd can support 4 viewers at maximum at the same time, where $\frac{1470}{366.2} \approx 4$.

3. If rockslcd is used, $Bwmemcpy = 1470\ MB/s$, then

$$T = \frac{Ndata}{Bwnetwork} + 2(\frac{Ndata}{Bwmemcpy}) = \frac{183.1}{Bwnetwork} + 2(\frac{183.1}{1470}) \leq 1$$
$$\Rightarrow Bwnetwork \geq 243.8\ MB/s = 1950.8\ Mbit/s = 1.9\ Gbit/s$$

   This means that the requirement of $Bwnetwork$ increases 33.2% at rockslcd. Memory overhead has an influence on the actual performance. The requirement of $Bwnetwork$ is more than the max bandwidth of 1 Giga Ethernet, so rockslcd cannot support one viewer without compression at 25 FPS over 1 Giga Ethernet.

4. If 100 GbE is used, or $Bwnetwork = 100\ Gb/s = 12.5\ GB/s$, how much bandwidth of memory copy is required to support 28 viewers at 25 FPS?

$$T = \frac{Ndata}{Bwnetwork} + 2(\frac{Ndata}{Bwmemcpy}) = \frac{183.1}{12.5 * 1024} + 2(\frac{183.1}{Bwmemcpy}) \leq 1/28$$

$$\Rightarrow Bwmemcpy \geq 17089.3\ MB/s = 16.7\ GB/s = 133.5\ Gbit/s$$

This shows that the bandwidth of memory copy is at least $16.7\ GB/s$, when the bandwidth consumption of shared applications is ignored. Now the peak bandwidth of DDR3-1600 is up to about $12\ GB/s$. So we can expect that peak memory bandwidth can meet this requirement. However, how many CPU frequencies are required to support $16.7\ GB/s$ memory copy?

$$Freqcpu = \frac{(Bwmemcpy * C)}{64/8} = \frac{(16.7G * 18)}{64/8} \approx 38\ GHz$$

It means that the required frequency of one single CPU is about 38 GHz. However, it's not achieved. We have no idea how long we can achieve it. One possible solution is to use multi-core CPUs, which are about 10 cores, so that multi-thread architecture has to be used.

5.3.3 Conclusion

- It is impossible for VNC model to support one viewer, where the size of one frame is 1600x1200 and FPS is 25 without compression in Giga Ethernet.
- It is impossible for VNC model to support 28 viewers at 25 FPS without compression, because it requires about 38 GHz CPU to handle memory copy even in 100 Gb Ethernet. Multi-thread has to be used when the number of viewers is up to 28.

Based on these conclusions, pixel compression and Multi-core CPUs must be used to share display content.

5.4 Sharing Display Content with Compression

5.4.1 Evaluation Equation for CPU and Network

When pixel compression is applied, the time (T) will contain the time of pixel compression. The equation is shown as follows.

$$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} + \frac{Ndata}{Bwmemcpy} \times (1 + \frac{1}{Ratio})$$

$$+ \frac{Npixel \times f \times Cyclesforonecomparison}{Frequency} \leq 1$$

Where Ratio represents the compression ratio of pixels (Ratio=uncompressed pixels/compressed pixels), Frequency stands for CPU frequency, and f represents the number of the comparison times for one pixel. $Cyclesforonecomparison$ is cycles of one memory read, one memory write and one pixel comparison. According to 18 cycles for one memory copy in the background section, it's reasonable to assume $Cyclesforonecomparison = 20$. In hextile encoding, one pixel must be compared 3 times at least. The first time is to get the background pixel and foreground pixel. The second time is for comparison with the background pixel. There is at least one pixel comparison in order to find one same colour rectangle. So it is reasonable to assume that $f \geq 3$.

5.4.2 Discussion

1. $Bwmemcpy \to \infty$

   This assumption is that the capability of CPU and memory systems is infinite. Namely, the time for reading and encoding pixels is close to 0. When 1 Gbit Ethernet network is used, $Bwnetwork = 125\ MB/s$.

   $$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} = \frac{183.1}{125} \times \frac{1}{Ratio} \leq 1 \Rightarrow Ratio \geq 1.5$$

   That means that the compression ratio is 1.5 when one viewer is at 25 FPS. This is easy to satisfy. For example, the compression ratio in our experimental videos is about 5. So it's possible to support one viewer at 25 FPS in Giga Ethernet.

   When the number of viewers is up to 28 and VNC model is used,

   $$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} = \frac{183.1}{125} \times \frac{1}{Ratio} \leq 1/28 \Rightarrow Ratio \geq 41$$

   This means that the size of the uncompressed pixels has to be at least 41 times than that of the compressed pixels. Hextile encoding is used to explain what this ratio means. Hextile encoding method encodes tiles into same colour rectangles, each of which consumes 6 bytes. One tile includes 16x16 pixels. Each tile uses one additional byte to show the number of rectangles. So if hextile encoding is used, the number of rectangles can be estimated.

   $$Ratio = \frac{16 \times 16 \times 4}{6 \times Nrectangle + 1} \geq 41 \Rightarrow Nrectangle \leq 4$$

   The number of rectangles in one tile is at most 4. That means that it's limited to applications having few different colours, such as static documents.

   When the number of viewers is up to 28 and MultiStream model is used,

   $$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} = \frac{183.1}{125} \times \frac{1}{Ratio} \leq 1 \Rightarrow Ratio \geq 1.5$$

   This means that the size of the uncompressed pixels has to be at least 1.5 times than the size of the compressed pixels. This is easier to achieve with MultiStream model than with VNC model.

   So when the capability of CPU and memory systems is infinite and Giga Ethernet is used, MultiStream model requires a little less ratio than VNC model.

2. If rockslcd is used, $Bwmemcpy = 1470\ MB/s$, then

   $$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} + \frac{Ndata}{Bwmemcpy} \times (1 + \frac{1}{Ratio})$$

$$+\frac{Npixel \times f \times Cyclesforonecomparison}{Frequency}$$

$$= \frac{183.1}{125} \times \frac{1}{Ratio} + \frac{183.1}{1470} \times (1 + \frac{1}{Ratio}) + \frac{1600 \times 1200 \times 3 \times 20}{3.2 \times 1024 \times 1024 \times 1024} \leq 1$$

$$\Rightarrow Ratio \geq 1.9$$

That means that rockslcd can support one viewer at 25 FPS, when Ratio is more than 1.9. However, it is difficult to reach it at rockslcd. The reason is that the applications and network transmission consume CPU cycles. As a result, peak memory bandwidth and CPU cycles are impossible to be used for sharing display content.

3. If $peak\ transfer\ rate\ of\ memory \to \infty$ and $Bwnetwork \to \infty$, how many number of viewers can support in one single 3.2 GHz 64-bit CPU?

   The assumption $peak\ transfer\ rate\ of\ memory \to \infty$ means that read or write can be done in one cycle. So $Bwmemcpy = 3.2 * 64/8 = 25.6\,GB/s = 26214.4\,MB/s$. $\frac{Ndata}{Bwmemcpy} = \frac{183.1}{26214.4} = 0.007$.

$$T = \frac{Ndata}{Bwmemcpy} \times (1 + \frac{1}{Ratio}) + \frac{Npixel \times f \times Cyclesforonecomparison \times Nviewer}{Frequency}$$

$$= 0.007 \times (1 + \frac{1}{Ratio}) + \frac{1600 \times 1200 \times 3 \times 20 \times Nviewer}{3.2 \times 1024 \times 1024 \times 1024} \leq \frac{1}{Nviewer}$$

$$\Rightarrow Nviwer \leq 5$$

   That means that 3.2 GHz CPU can support only 5 viewers at maximum, even if the bandwidth of memory and network is infinite.

4. When $Bwmemcpy = 2\,GB/s$, and $Bwnetwork = 10\,Gb/s$, is it possible to support 28 viewers?

   This assumption is that the bandwidth of memory copy is able to support $2\,GB/s$ and the peak bandwidth of the network is $10\,Gb/s$. A 64-bit 4 GHz CPU can read or write 32 GB data per second when read or write can be done each cycle. The cycles of one memory copy is about 18. So it's reasonable to assume $Bwmemcpy = 2\,GB/s$.

   If VNC model is used,

$$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} + \frac{Ndata}{Bwmemcpy} \times (1 + \frac{1}{Ratio})$$

$$+\frac{Npixel \times f \times Cyclesforonecomparison}{Frequency}$$

$$T = \frac{183.1}{10 \times 1024 \div 8} \times \frac{1}{Ratio} + \frac{183.1}{2 \times 1024} \times (1 + \frac{1}{Ratio})$$

$$+\frac{1600 \times 1200 \times 3 \times 20}{3.2 \times 1024 \times 1024 \times 1024} \leq 1/28$$

$$\Rightarrow Ratio = \phi.$$

   ϕ means that this ratio is impractical because the ratio is negative. That means it's impossible to implement 28 viewers at 25 FPS with 3.2 GHz CPU and a single thread at the same time.

   If MultiStream model is used,

$$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} + \frac{Ndata}{Bwmemcpy} \times (1 + \frac{1}{Ratio})$$

$$+\frac{Npixel \times f \times Cyclesforonecomparison}{Frequency}$$

$$T = \frac{183.1}{10 \times 1024 \div 8} \times \frac{1}{Ratio} + \frac{183.1}{2 \times 1024} \times (1 + \frac{1}{Ratio})$$

$$+\frac{1600 \times 1200 \times 3 \times 20}{3.2 \times 1024 \times 1024 \times 1024} \leq 1$$

$$\Rightarrow Ratio \geq 1.$$

Ratio must be at least more than 1. This shows that it's possible for MultiStream model to support 28 viewers at 25 FPS. In contrast with VNC model, MultiStream model needs less Ratio. From this discussion, we can know that MultiStream model is more able to support 28 viewers when $Bwmemcpy = 2\ GB/s$ and $Bwnetwork = 10\ Gb/s$.

5. $Bwmemcpy = 2\ GB/s$ and Multi-core CPUs

When Multi-core CPUs are introduced and multi-thread is used at 28 viewers, we assume that it is completely parallel in order to handle memory copy and pixel encoding. The speedup factor of memory bandwidth and pixel encoding is the number of CPU cores, P=28. It's also assumed that peak bandwidth is used in 10 Gb Ethernet. Transmission over network cannot be parallel.

If VNC model is used,

$$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} + \frac{Ndata}{Bwmemcpy} \times (1 + \frac{1}{Ratio}) \times \frac{1}{P}$$

$$+\frac{Npixel \times f \times Cyclesforonecomparison}{Frequency} \times \frac{1}{P}$$

$$T = \frac{183.1}{10 \times 1024 \div 8} \times \frac{1}{Ratio} + \frac{183.1}{2 \times 1024} \times (1 + \frac{1}{Ratio}) \times \frac{1}{28}$$

$$+\frac{1600 \times 1200 \times 3 \times 20}{3.2 \times 1024 \times 1024 \times 1024} \times \frac{1}{28} \leq 1/28$$

$$\Rightarrow Ratio \geq 7.4$$

That means that it is feasible to support 28 viewers at 25 FPS in multi-core CPUs and 10 Gb Ethernet, because the compression ratio can be acceptable. However, it is required to implement highly parallel computing for sharing display content in order to utilize multi-core CPUs.

If MultiStream model is used,

$$T = \frac{Ndata}{Bwnetwork} \times \frac{1}{Ratio} + \frac{Ndata}{Bwmemcpy} \times (1 + \frac{1}{Ratio}) \times \frac{1}{P}$$

$$+\frac{Npixel \times f \times Cyclesforonecomparison}{Frequency} \times \frac{1}{P}$$

$$T = \frac{183.1}{10 \times 1024 \div 8} \times \frac{1}{Ratio} + \frac{183.1}{2 \times 1024} \times (1 + \frac{1}{Ratio}) \times \frac{1}{28}$$

$$+\frac{1600 \times 1200 \times 3 \times 20}{3.2 \times 1024 \times 1024 \times 1024} \times \frac{1}{28} \leq 1$$

$$\Rightarrow Ratio \geq 1$$

This shows that MultiStream model is able to support 28 viewers at 25 FPS when Multi-core CPUs are used and $Bwmemcpy = 2\ GB/s$.

As a result, it is possible for both VNC model and MultiStream model to support 28 viewers at 25 FPS. But MultiStream model needs less compression ratio.

Assumption	VNC Model	MultiStream Model
$Bwmemcpy = 2\,GB/s$ and $Bwnetwork = 10\,Gb/s$	$Ratio = \phi$	$Ratio \geq 1$
$Bwmemcpy = 2\,GB/s$ and Multi-core CPUs	$Ratio \geq 7.4$	$Ratio \geq 1$

Table 5.4: The Required Minimum Ratio to Achieve 25 FPS for 28 Viewers

5.4.3 Conclusion

1. It is possible to support one viewer at 25 FPS and 1600×1200 each frame with compression in Giga Ethernet, such as the rockslcd platform (3.2 GHz CPU and DDR2-533 memory).

2. It is impossible for VNC model to support 28 viewers at 25 FPS and 1600×1200 resolution per frame with one single thread when $Bwmemcpy = 2\,GB/s$, and $Bwnetwork = 10\,Gb/s$. It is possible for VNC model to support 28 viewers at 25 FPS for the 1600×1200 frame with compression in 10 Gb Ethernet when $Bwmemcpy = 2\,GB/s$ and Multi-core CPUs are used.

3. It is possible for MultiStream model to support 28 viewers at 25 FPS with one single thread when $Bwmemcpy = 2\,GB/s$, and $Bwnetwork = 10\,Gb/s$. It is possible for MultiStream model to support 28 viewers at 25 FPS with 10 Gb Ethernet when $Bwmemcpy = 2\,GB/s$ and Multi-core CPUs are used.

The required minimum ratio is listed in Table 5.4. From this table, the minimum ratio of MultiStream model is less than that of VNC model. Although the MultiStream model is applied at low resolution in the dissertation, the architecture of MultiStream is also helpful to improve the performance of the VNC model further. The architecture of VNC can separate capturing display content from distributing display content.

Chapter 6

Conclusion

Hyper-display based collaboration requires sharing display content at low resolution and high resolution. We argue that a pixel level model is well suited to share display content. This model provides compatibility with existing applications. However, this model also introduces some problems, such as high CPU and network usage. This dissertation has discussed the problems when display content is shared at low resolution and high resolution. Two principles are presented about sharing display content at low resolution and high resolution. Each of them is described from two dimensions, network bandwidth and processing.

Two different architectures for sharing display content at low resolution are a centralized, pull-model, non-distributed architecture and a decentralized, push-model, distributed architecture. We conclude that it is possible both in principle and in practice for network bandwidth to support tens of clients with a standard resolution desktop with emerging network technology in a centralized, pull-model, non-distributed architecture. It is not a case using a single core CPU. We also conclude that multi-core CPUs or many-core GPUs must be applied to a centralized, pull-model, non-distributed architecture. It is possible in principle and in practice for MultiStream to support hundreds of clients today and thousands with emerging network technology in a de-centralized, push-model, distributed architecture, and it is possible in principle and in practice for MultiStream to be handled with one single core CPU in a decentralized, push-model, distributed architecture.

The X VNC server is a centralized, non-distributed architecture. The principle is described as follows. It is impossible in principle and in practice to drive a tens of mega-pixels display wall desktop at 25 FPS without using compression and with 1 Gbit Ethernet network. It is possible in principle to support it with emerging network technology. It is possible in principle to support it with compression today. It is impossible in principle and in practice to drive a tens of mega-pixels display wall desktop at 25 FPS with a single core. It is possible in principle to drive it at 25 FPS with emerging technology.

This PHD progress designs and implements MultiStream and display wall desktops to share display content, using media streaming and VNC protocol respectively. MultiStream is designed for display content at low resolution. MultiStream is a cross-platform solution to sharing display content over various display devices, which is designed to share display content over devices which have architectural and performance differences. By using standard media players and video stream formats we reduce or avoid several of these complexities and performance bottlenecks. Display content is encoded as continuous video streaming, and a video server processes and distributes customized or fixed rate videos to viewers. High compression ratio and the separated server node improve the performance of sharing display content.

A display wall desktop is used to fill a display wall. This desktop is a high resolution 2D X server desktop environment, which uses the VNC protocol. It is used to utilize display wall to implement more display space. The output of all VNC clients running in all tiles of display wall is put together so that a seamless X desktop is provided. VNC protocol uses lossless compression. Applications and the server run in the same node so that applications have to compete for computing resources against the server. According to the performance evaluation, a display wall desktop is CPU-intensive. The critical parts are data movement and pixel encoding. Three different approaches are applied to display wall desktops. These approaches use instruction level improvement, a multi-thread architecture and GPUs. According to the experimental results, a multi-thread architecture gains the best improvement.

Chapter 7

Future Work

This chapter will present some possible lines for future work in a hyper-display based environment.

An evaluation system is required to be built in order to evaluate the performance of a high resolution display wall. Our evaluation system is derived from the slow motion evaluation method. Although we have played back media videos to evaluate our desktop system, this method is suited well to low resolutions. When the resolution increases, applications need more CPU cycles and have to compete with the server for CPU resources. This is the reason that we don't use the same resolution as the resolution of the desktop. It shows that playing back videos is not fit for a high resolution desktop. At the same time, a typical usage is not evaluated in a display wall, such as navigating documents and viewing images. A new evaluation system is required to be investigated.

The performance of a high resolution display wall desktop is required to be improved further. I argue that using GPU is still one possible line of improvement. Although an implementation of display wall desktop is done with CUDA, the performance is a little lower than that of the Multi-thread architecture. This dissertation has demonstrated three improvement approaches separately to the high resolution display wall desktop, but they were not implemented together. In the future, the further improvements must be implemented together.

A greater compression ratio is required. A display wall is a cluster-based tiled display, which is scalable and economical. However, computing distribution and display distribution lead to the complexity of running applications at a display wall and low performance, especially at high resolution. All of improvements are related to the implementation of a high resolution desktop using VNC protocol. VNC protocol supports pixel compression to save network bandwidth. But nothing does with the compression of X11 protocol. NX can achieve 1000:1 compression of X11 data. It shows that a greater compression ratio can come from X11 data in addition to pixel compression.

3D applications are an important application area at a display wall. It is necessary for a display wall to support 3D applications at a display wall desktop. However, VNC protocol cannot support 3D directly. The possible solution is to forward 3D commands to tiles at a display wall, and the tiles render 3D output.

Usage and performance of mobile display devices are required to be demonstrated further at a display wall. Although MultiStream supports mobile devices to view display content, we didn't evaluate system performance, such as how many devices can be supported in a wireless network and what is the adaption performance of display content from one resolution to another resolution.

How many pixels are best suited to display wall collaboration? We use a display wall desktop at 22 mega-pixels now. It is possible to change resolutions to tradeoff the visualization space and the frame rate. We require investigation of how resolutions affect information navigation.

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