Equalizer 2.0 – Convergence of a Parallel Rendering Framework

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Abstract—Developing complex, real world graphics applications which leverage multiple GPUs and computers for interactive 3D rendering tasks is a complex task. It requires expertise in distributed systems and parallel rendering in addition to the application domain itself. We present a mature parallel rendering framework which provides a large set of features, algorithms and system integration for a wide range of real-world research and industry applications. Using the Equalizer parallel rendering framework, we show how a wide set of generic algorithms can be integrated in the framework to help application scalability and development in many different domains, highlighting how concrete applications benefit from the diverse aspects and use cases of Equalizer. We present novel parallel rendering algorithms, powerful abstractions for large visualization setups and virtual reality, as well as new experimental results for parallel rendering and data distribution.

Index Terms—Parallel Rendering, Scalable Visualization, Cluster Graphics, Immersive Environments, Display Walls

1 Introduction

The Equalizer parallel rendering framework, first presented in [8], has demonstrated its general versatility and the usefulness of its minimally-intrusive design in a variety of applications and projects. In particular, the integration of large-scale parallel rendering algorithms, APIs for developing complex distributed applications, and many individual features make Equalizer a unique, open source framework to develop visualization applications for virtually any type of setup and use case. While individual applications and case studies using the framework, as well as new algorithms and system components extending it have been presented since the initial release of Equalizer, many features and functionalities have not been published yet and are presented here. In this report, we thus present an updated comprehensive review of the integration of research, application use cases and commercial developments with respect to Equalizer as well as novel comparative experimental results of its scalability features.

We present novel algorithms for parallel rendering which did not appear in a separate publication, including pixel and sub-pixel decompositions, dynamic frame resolution, tunable sort-first load-balancing parameters, frame-rate equalization, thread synchronization modes for multi-GPU rendering, a powerful abstraction for multi-view rendering on arbitrary display setups, dynamic focus distance and asymmetric eye positions for VR, parallel pixel streaming to tiled display walls, as well as a fully-fledged data distribution API with compression and reliable multicast.

The remainder of this paper is structured as follows: First we provide an update on related work since the introduction of Equalizer. The main body of this paper then presents new performance features, VR algorithms, usability features to build complex applications, an overview of the underlying Collage network library and a summary of the main Equalizer-based applications. A result section presents new experiments, followed by the discussion and conclusion.

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2 Related Work

In 2009 we presented Equalizer [8], which introduced the architecture of a generic parallel rendering framework and summarized our work in parallel rendering. Since then, an extensive Programming and User Guide provides in-depth documentation on using and programming Equalizer [6]. We assume these two publications and their references as a starting point, and focus on the new work published since 2009.

The concept of transparent OpenGL interception popularized by WireGL and Chromium [21] has received little attention since 2009. While some commercial implementations such as TechViz and MechDyne Conduit continue to exist, on the research side only ClusterGL [30] has been presented. ClusterGL employs the same approach as Chromium, but delivers a significantly faster implementation of transparent OpenGL interception and distribution for parallel rendering. CGLX [5] tries to bring parallel execution transparently to OpenGL applications, by emulating the GLUT API and intercepting certain OpenGL calls. In contrast to frameworks like Chromium and ClusterGL which distribute OpenGL calls, CGLX follows the distributed application approach. This works transparently for trivial applications, but quickly requires the application developer to address the complexities of a distributed application, when mutable application state needs to be synchronized across processes. For realistic applications, writing parallel applications remains the only viable approach for scalable parallel rendering, as shown by the success of Paraview, Visit and various Equalizer-based applications.

On the other hand, software for driving and interacting with tiled display walls has received significant attention, including Sage [29] and Sage 2 [26] in particular. Sage was built entirely around the concept of a shared framebuffer where all content windows are separate applications using pixel streaming. It is no longer actively supported. Sage 2 is a complete, browser-centric

(a) (b) (c)

Fig. 1: Example Equalizer applications: (a) 192 Megapixel CAVE at KAUST running RTNeuron, (b) Immersive HMD with external tracked and untracked views running RTT DeltaGen for virtual car usability studies, and (c) Cave2 running a molecular visualization.

reimplementation where each application is a web application distributed across browser instances. DisplayCluster [23], and its continuation Tide [3], also implement the shared framebuffer concept of Sage, but provide a few native content applications integrated into the display servers. All these solutions implement a scalable display environment and are a target display platform for scalable 3D graphics applications.

Equalizer itself has received significant attention within the research community. Various algorithms to improve the parallel rendering performance have been proposed: compression and region of interest during compositing [25], load-balancing resources for multi-display installations [11], asynchronous compositing and NUMA optimizations [7], as well as work queueing [32]. Additionally, complex large scale and out-of-core multiresolution rendering approaches have been parallelized and implemented with Equalizer [18], [19], demonstrating the feasibility of the framework to be used with complex rendering algorithms and 3D model representations.

Furthermore, various applications and frameworks have used Equalizer for new research in visualization. On the application side, RTT Deltagen, Bino, Livre and RTNeuron [20] are the most mature examples and are presented in Section 8. On the framework side, Omegalib [13], a framework used in the Cave2, made significant progress in integrating 2D collaborative workspaces like Sage 2 with 3D immersive content. Lambers et.al. developed a framework for visualizing remote sensing data [24] on large displays and immersive installations.

3 Fundamentals

The core task of developing an Equalizer application is to separate the rendering code from the application logic. The application main thread will execute its main loop as before, but instead of issuing rendering calls it will request a frame to be rendered from Equalizer. Depending on the configuration, Equalizer will then decompose and synchronize the rendering tasks. The application rendering code is executed in parallel under a given render context, which is the core entity abstracting the application-specific rendering algorithm from the system-specific configuration. This render context formalizes the minimal abstraction for parallel rendering, and specifies:

Buffer OpenGL-style read and draw buffer as well as color mask. These parameters are influenced by the current eye pass, eye separation and anaglyphic stereo settings.

Viewport Two-dimensional pixel viewport restricting the rendering area. The pixel viewport is influenced by the destination viewport and viewports set for sort-first decompositions.

Frustum Frustum parameters as defined by glFrustum. Typically the frustum is used to set up the OpenGL projection matrix. The frustum is influenced by the destinations view definition, sort-first, pixel and subpixel decomposition, tracking head matrix and the current eye pass.

Head Transformation A transformation matrix positioning the frustum. For planar views this is an identity matrix. In immersive rendering, it is normally used to set up the 'view' part of the modelview matrix, before static light sources are defined.

Range A one-dimensional range with the interval [0..1]. This parameter is optional and should be used by the application to render only the appropriate subset of its data for sort-last rendering.

View The view object from the logical rendering rendering configuration (Section 6.1). Holds view-specific data, such as camera, model or any other application state.

An Equalizer configuration determines how the application is executed in parallel. It has three parts: A resource section describing the physical rendering resources (node, pipe, window, channel), a section describing the visualization setup (Section 6.1), and a compound section describing how these resources are to be used for rendering. Compounds describe the rendering task decomposition and result recomposition, and their algorithm has been introduced in [8].

Our execution model is fully asynchronuous, and only introduces synchronization points when strictly needed. The main synchronization points are: configured swap barriers between a set of output channels which have to display simultaneously, the availability of input frames for scalable rendering, and a task synchronization to prevent runaway of the main loop execution. By default, Equalizer keeps up to one frame of latency in execution, that is, some resource might render the next frame while others are still finishing the current. Nonetheless, resources which are ready will immediately display their result. This asynchronous execution architecture, coupled with a frame of latency, allows pipelining of many operations, such as the application event processing, task computation and load balancing, rendering, image readback, compression, network transmission, and compositing. It also hides small imbalances in the task distribution, as they can average out over multiple frames. It is fundamental to provide optimal performance, in particular for larger cluster sizes.

4 Performance Features

4.1 New Decomposition Modes

The initial version of Equalizer implemented the basic sort-first (2D), sort-last (DB), stereo (EYE) and multilevel decompositions [8]. In the following we present new decomposition modes and motivate their use case, which bring the overall feature set way beyond the typical sort-first and sort-last rendering modes. Figure 2 provides an overview of the new modes. The compound concept to set up scalable rendering is presented in [8].

4.1.1 Time-Multiplex

Time-multiplexing (Figure 2a), also called AFR or DPlex, was first implemented in [2] for shared memory machines. It is however a better fit for distributed memory systems, since the separate memory space makes concurrent rendering of different frames easier to implement. While it increases the framerate linearly, it does not decrease the latency between user input and the corresponding output. Consequently, this decomposition mode is mostly useful for non-interactive rendering, e.g., for movie generation. It is transparent to Equalizer applications, but does require the configuration latency to be equal or greater than the number of source channels. Furthermore, to work in multi-threaded, multi-GPU configurations, the application needs to support running the rendering threads asynchronously (Section 4.3.4). The output frame rate of the destination channel may be smoothened using a *frame rate equalizer* (Section 4.2.5).

DPlex is configured by restricting the source compounds to a *phase* (offset) of a certain *period* (number of skipped frames) of the destination channel's rendering. All output frames of the source channels may use the same name, as each output frame only is available at a distinct rendered frame for input. The period/phase decomposition may also be used for other means, e.g., to have one channel render at half the frame rate on an underpowered control workstation for a tiled display wall.

4.1.2 Tiles and Chunks

Tile (Figure 2b) and chunk decompositions are a variant of sort-first and sort-last rendering, respectively. They are implemented via the tile_equalizer and chunk_equalizer compounds, which decompose the scene into a predefined set of fixed-size image tiles or database ranges, respectively. The resulting tasks, or work packages, are queued and processed by all source channels by polling a server-central queue. Prefetching ensures that the task communication overlaps with rendering. As shown in [32] and the results, these modes can provide better performance due to being implicitly, i.e., inherently load-balanced, as long as there is an insignificant overhead for the render task setup. This mode is transparent to Equalizer applications.

Tile and chunk compounds are configured through output and input queues, which behave similarly to compositing frames. A single output queue configures the tile or chunk size and generates the work packages on the destination compound. Each source has an input queue of the same name, which consumes items from the output queue. Each work item generates a separate draw and readback task, and one input assemble image on the destination channel.

4.1.3 Pixel

Pixel compounds (Figure 2c) decompose the destination channel by interleaving rows or columns in image space. They are a variant of sort-first decomposition which works well for fill-limited applications which are not geometry bound, for example direct volume rendering. Source channels cannot reduce geometry load through view frustum culling, since each source channel has almost the same frustum. However, the fragment load on all source channels is reduced linearly and well load-balanced due to the interleaved distribution of pixels. This functionality is transparent to Equalizer applications, and the default compositing uses the stencil buffer to blit pixels onto the destination channel.

Pixel compounds are configured similarly to sort-first compounds, except that instead of decomposing the *viewport*, they decompose a *pixel* kernel. The kernel is a 2D structure describing the shape and sampled pixel within the shape in the format *[x y width height]*, that is, a source compound selects the pixel *x, y* within a decomposition of size *width, height*.

4.1.4 Subpixel

Subpixel compounds (Figure 2d) are similar to pixel compounds, but they decompose the work for a single pixel, for example with Monte-Carlo ray tracing, FSAA or depth of field rendering. Composition typically uses accumulation and averaging of all computed fragments for a pixel. This feature is not fully transparent to the application, since it needs to adapt (jitter or tilt) the frustum based on the iteration executed.

Subpixel compounds are configured similarly to pixel compounds, but instead of a *pixel* kernel they decompose a *subpixel* kernel in the format *[index, size]*, describing which subpixel of *size* samples a source produces. By default, the output frames are averaged on the destination channel.

4.2 Equalizers

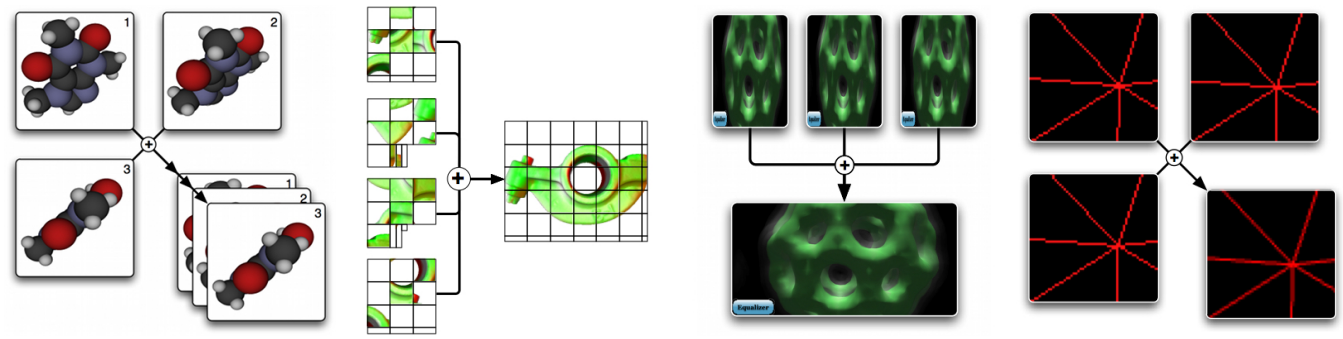
Equalizers are an addition to compound trees. They modify parameters of their respective subtree at runtime to dynamically optimize the resource usage, by each tuning one aspect of the decomposition. Due to their nature, they are transparent to application developers, but might have application-accessible parameters to tune their behavior. Resource equalization is the critical component for scalable parallel rendering, and therefore the eponym for the Equalizer project name.

4.2.1 Sort-First and Sort-Last Load Balancing

Sort-first (Figure 3a) and sort-last load balancing are the most obvious optimizations for these parallel rendering modes. Our load equalizers are fully transparent for application developers; that is, they use a reactive approach based on past rendering times. This assumes a reasonable frame-to-frame coherence. Equalizer implements two different algorithms, a load_equalizer and a tree_equalizer. Both implementations modify the viewport or range of their direct child compounds. The result section provides some evidence on the strengths and weaknesses of both algorithms.

The load_equalizer stores a 2D or 1D grid of the load, mapping the load of each channel. The load is stored in normalized 2D/1D coordinates using $\frac{time}{area}$ as the load, the contributing source channels are organized in a binary tree, and then the algorithm balances the two branches of each level by equalizing the integral over the cost area map on each side.

The tree_equalizer also uses a binary tree for recursive load balancing. It computes the accumulated render time on all nodes of the tree, and uses this to allocate an equal render time to each



```
compound {
  channel "destination"
  framerate_equalizer {}
  compound {
    channel "source1"
    phase 0 period 3
    outputframe { name "frame" }
  }
  compound {
    channel "source2"
    phase 1 period 3
    outputframe { name "frame" }
  }
  compound {
    channel "source3"
    phase 2 period 3
    outputframe { name "frame" }
  }
  inputframe { name "frame" }
}
```

(a) Time-Multiplex

```
compound {
  channel "destination"
  outputtiles {
    name "queue"
    size [ 64 64 ]
  }
  compound {
    channel "destination"
    inputtiles { name "queue" }
  }
  compound {
    channel "source1"
    inputtiles { name "queue" }
    outputframe {}
  }
  compound {
    channel "source2"
    inputtiles { name "queue" }
    outputframe {}
  }
  compound {
    channel "source3"
    inputtiles { name "queue" }
    outputframe {}
  }
  inputframe { name "frame.source1" }
  inputframe { name "frame.source2" }
  inputframe { name "frame.source3" }
}
```

(b) Tiles

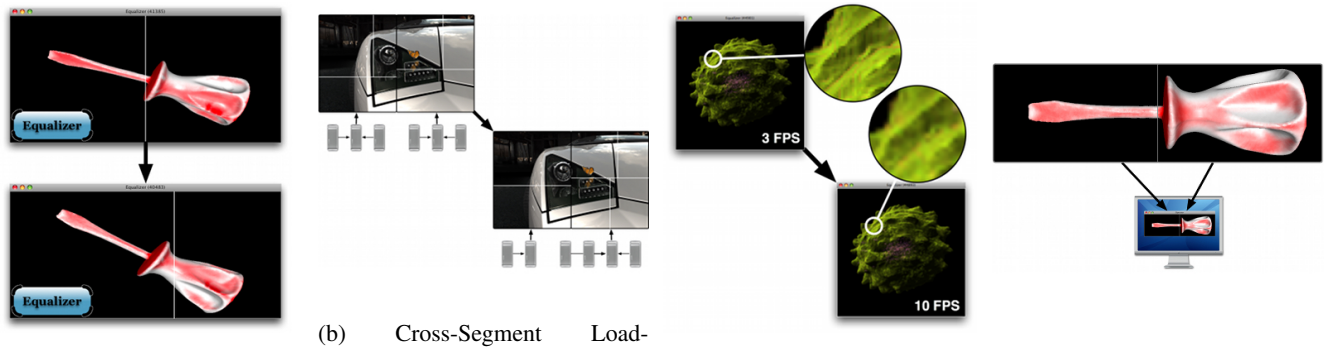
```
compound {
  channel "dest"
  compound {
    channel "dest"
    pixel [ 0 0 3 1 ]
    outputframe { type texture }
  }
  compound {
    channel "source1"
    pixel [ 1 0 3 1 ]
    outputframe {}
  }
  compound {
    channel "source2"
    pixel [ 2 0 3 1 ]
    outputframe {}
  }
  inputframe { name "frame.dest" }
  inputframe { name "frame.source1" }
  inputframe { name "frame.source2" }
}
```

(c) Pixel

```
compound {
  channel "dest"
  compound {
    channel "dest"
    subpixel [ 0 3 ]
    outputframe { type texture }
  }
  compound {
    channel "source1"
    subpixel [ 1 3 ]
    outputframe {}
  }
  compound {
    channel "source2"
    subpixel [ 1 3 ]
    outputframe {}
  }
  inputframe { name "frame.dest" }
  inputframe { name "frame.source1" }
  inputframe { name "frame.source2" }
}
```

(d) Subpixel

Fig. 2: New Equalizer task decomposition modes and their compound descriptions for parallel rendering



(a) Load-Balancing (b) Cross-Segment Load-Balancing (c) Dynamic Frame Resolution (d) Monitoring

Fig. 3: Runtime modifications

subtree. It makes no assumption of the load distribution in 2D or 1D space, it only tries to correct the imbalance in render time.

Both equalizers implement tuneable parameters allowing application developers to optimize the load balancing based on the characteristics of their rendering algorithm:

Split Mode configures the tile layout: horizontal or vertical stripes, and 2D, a binary tree split alternating the split axis on each level, resulting in compact 2D tiles.

Damping reduces frame-to-frame oscillations. The equal load distribution within the region of interest assumed by the load equalizer is in reality not equal, causing the load balancing to overshoot. Damping is a normalized scalar defining how much of the computed delta from the previous position is applied to the new split.

Resistance eliminates small deltas in the load balancing step. This might help the application to cache visibility computations since the frustum does not change each frame.

Boundaries define the modulo factor in pixels onto which a load split may fall. Some rendering algorithms produce artefacts related to the OpenGL raster position, e.g., screen door transparency, which can be eliminated by aligning the boundary to the pixel repetition. Furthermore, some rendering

algorithms are sensitive to cache alignments, which can again be exploited by chosing the corresponding boundary.

4.2.2 Dynamic Work Packages

The package equalizers implement client-affinity models for tile and chunk compounds (Section 4.1.2). A tile_equalizer or chunk_equalizer creates the packages and changes the assignment of them to individual nodes, based on an affinity model specified in the equalizer. In [32], we explore this approach in detail.

4.2.3 Cross-Segment Load Balancing

Cross-segment load balancing (CSLB, Figure 3b) optimizes resource allocation of n rendering resources to m output channels (with $n \geq m$). A view equalizer works in conjunction with load equalizers balancing the individual output channels. It monitors the usage of shared source channels across outputs and activates them to balance the rendering time of all outputs. CSLB is unique in that it supports load balancing for planar and non-planar visualization systems, as well as a flexible allocation of rendering resources to individual output channels. In [11], we provide a detailed description and evaluation of our algorithm and show that it significantly improves performance over a static allocation.

4.2.4 Dynamic Frame Resolution

The DFR equalizer (Figure 3c) provides a functionality similar to dynamic video resizing [27], that is, it maintains a constant framerate by adapting the rendering resolution of a fill-limited application. In Equalizer, this works by rendering into a source channel (typically on a FBO) separate to the destination channel, and then scaling the rendering during the transfer (typically through an on-GPU texture) to the destination channel. The DFR equalizer monitors the rendering performance and accordingly adapts the resolution of the source channel and zoom factor for the source to destination transfer. If the performance and source channel resolutions allow, this will not only subsample, but also supersample the destination channel to reduce aliasing artefacts.

4.2.5 Frame Rate Equalizer

The framerate equalizer smoothens the output frame rate of a destination channel by instructing the corresponding window to delay its buffer swap to a minimum time between swaps. This is regularly used for time-multiplexed decompositions, where source channels tend to drift and finish their rendering unevenly distributed over time. This equalizer is however fully independent of DPlex compounds, and may be used to smoothen irregular application rendering algorithms.

4.2.6 Monitoring

The monitor equalizer (Figure 3d, Figure 4) allows to reuse the rendering on another channel, typically for monitoring a larger setup on a control workstation. Output frames on the display channels are connected to input frames on a single monitoring channel. The monitor equalizer changes the scaling factor and offset between the output and input, so that the monitor channel has the same, but typically downscaled view, as the originating segments.

4.3 Optimizations

4.3.1 Region of Interest

The region of interest is the screen-space 2D bounding box enclosing the data rendered by a single resource. We use an application-provided ROI to optimize the load_equalizer as well as image compositing in our framework. The load equalizer uses the ROI to refine its load grid to the regions containing data. The compositing code uses the ROI to minimize image readback and network transmission. In [25] and [7], we provide the details of the algorithm, and show that using ROI can quadruple the rendering performance, in particular for the costly compositing step in sort-last rendering.

4.3.2 Asynchronous Compositing

Asynchronous compositing is pipelining the rendering with compositing operations, by executing the image readback, network transfer and image assembly from threads running in parallel to the rendering threads. In [7], we provide the details of the implementation and experimental data showing an improvement of the rendering performance of over 25% for large node counts.

4.3.3 Download and Compression Plugins

Compression for the compositing step is critical for performance. This not only applies to the well-researched network transfer step, but also for the transfer between GPU and CPU. Equalizer supports a variety of compression algorithms, from very fast run-length encoding (RLE) and YUV subsampling on the GPU to JPEG compression. These algorithms are implemented as runtime-loaded plugins, allowing easy extension and customization to application-specific compression. In [25], we show this to be a critical step for interactive performance at scale.

4.3.4 Thread Synchronization Modes

Different applications have different degrees on how decoupled and thread-safe the rendering code is from the application logic. For full decoupling all mutable data has to have a copy in each render thread, which is not feasible in most applications and large data scenarios. We implement three threading modes: Full synchronization, draw synchronization and asynchronous. Note that the execution between node processes is always asynchronous, for up to latency frames.

In full synchronization, all threads always execute the same frame; that is, the render threads are unlocked after Node::frameStart, and the node is blocked for all render threads to finish the frame before executing Node::frameFinish. This allows the render threads to read shared data from all their operations, but provides the slowest performance.

In draw synchronization, the node thread and all render threads are synchronized for all frameDraw operations; that is, Node::frameFinish is executed after the last channel is done drawing. This allows the render threads to read shared data during their draw operation, but not during compositing. Since compositing is often independent of the rendered data, this is the default mode. This mode allows to overlap compositing with rendering and data synchronization on multi-GPU machines.

In asynchronous execution, all threads run asynchronously. Render threads may work on different frames at any given time. This mode is the fastest, and requires the application to have one instance of each mutable object in each render thread. It is required for scaling time-multiplex compounds on multi-GPU machines.

5 VIRTUAL REALITY

Virtual Reality is an important field for parallel rendering, which requires special attention to support it as a first-class citizen in a generic parallel rendering framework. Equalizer has been used in many virtual reality installations, such as the Cave2 [14], the high-resolution C6 CAVE at the KAUST visualization laboratory, and head-mounted displays (Figure 1). In the following we lay out the features needed to support these installations.

5.1 Head Tracking

Head tracking is fundamental to support immersive installations. We support multiple, independent tracked views through the observer abstraction (Section 6.1). Built-in VRPN support enables direct, application-transparent configuration of a VRPN tracker device. Alternatively, applications can provide a 4×4 tracking matrix. Both CAVE-like tracking with fixed projection surfaces and HMD tracking with moving displays are implemented.

5.2 Dynamic Focus Distance

To our knowledge, all parallel rendering systems have the focal plane coincide with the physical display surface. For better viewing comfort, we introduce a new dynamic focus mode, where the application defines the distance of the focal plane from the observer, based on the current *lookat* distance. Initial experiments show that this provides better viewing comfort, in particular for objects placed in front of the physical displays.

5.3 Asymmetric Eye Position

Traditional head tracking computes the left and right eye positions by using an interocular distance. However, human heads are not symmetric, and by measuring individual users a more precise frustum can be computed. Equalizer supports this through the optional configuration of individual 3D eye translations relative to the tracking matrix.

5.4 Model Unit

This feature allows applications to specify a scaling factor between the model and the real world, to allow exploration of macroscopic or microscopic worlds in virtual reality. The unit is per view, allowing different scale factors within the same application. It scales both the specified projection surface as well as the eye position (and therefore separation) to achieve the necessary effect.

5.5 Runtime Stereo Switch

Applications can switch each view between mono and stereo rendering at runtime, and run both monoscopic and stereoscopic views concurrently (Figure 1 (b)). This switch does potentially involve the start and stop of resources and processes for passive stereo or stereo-dependent task decompositions (Section 6.2).

6 USABILITY FEATURES

In this section we present features motivated by real-world application use cases, i.e., new functionalities rather then performance improvements. We motivate the use case, explain the architecture and integration into our parallel rendering framework, and, where applicable, show the steps needed to use this functionality in applications.

6.1 Physical and Logical Visualization Setup

Real-world visualization setups can be complex. An abstract representation of the display system simplifies the configuration process. Applications often have the need to be aware of spatial relationships of the display setup, for example to render 2D overlays or to configure multiple views on a tiled display wall.

We addressed this need through a new configuration section interspersed between the node/pipe/window/channel hardware resources and the compound trees configurating the resource usage for parallel rendering.

A typical installation consists of one projection canvas, which is one aggregated projection surface, e.g., a tiled display wall or a CAVE. Desktop windows are considered a canvas. Each canvas is made of one or more segments, which are the individual outputs connected to a display or projector. Segments can be planar or non-planar to each other, and can overlap or have gaps between each other. A segment is referencing a channel, which defines the output area of this segment, e.g., on a DVI connector connected to a projector. This abstraction covers all use cases from simple windows, tiled display walls with bezels, to non-planar immersive systems with edge-blending.

A canvas can define a frustum, which will create default, planar sub-frusta for all of its segments. A segment can also define a frustum, which overrides the canvas frustum, e.g., for non-planar setups such as CAVEs or curved screens. These frusta describe a physically-correct display setup for a Virtual Reality installation. A canvas may have a software or hardware swap barrier, which will synchronize the rendering of all contributing GPUs. The software barrier executes a glFinish to ensure the GPU is ready to swap, a Collage barrier (Section 7.4) to synchronize all segments, and the swap buffers call followed by a glFlush to ensure timely execution of the swap command. The hardware swap barrier is implemented using the NV_swap_group extension.

On each canvas, the application can display one or more views. A view is used in the sense of the MVC pattern. The view class is available to applications to define view-specific data for rendering, e.g., a scene, viewing mode or camera. The application process manages this data, and the render clients receive it for rendering.

A layout groups one or more views which logically belong together. A layout is applied to a canvas. The layout assignment can be changed at run-time by the application. The intersection between views and segments defines which output channels are available, and which frustum they should use for rendering. These output channels are then used as destination channels in a compound. They are automatically created during configuration.

An observer looks at one or more views. It is described by the observer position in the world and its eye separation. Each observer has its own stereo mode, focus distance and eye positions. This allows to have untracked views and multiple tracked views, e.g., two HMDs, in the same application.

Figure 4 shows RTT Deltagen running an example multi-segment, multi-view setup driven by eight rendering nodes. The main tiled display wall canvas uses four LCD segments showing one layout with four views, which do not align on the segment boundaries. This setup creates seven destination channels. The configuration provides multiple, run-time configurable layouts. It is driven from the control host on the right, which shows four views, each in their own canvas and segment windows with a single-view layout each. One view on the control host synchronizes its content (model and camera) with one view on the display wall through Collage objects. The control host allows

Fig. 4: A 2x2 tiled display wall and control host rendering four independent views driven by an eight node visualization cluster

full model modifications and all workflows supported within the standalone Deltagen application, and all changes are synchronized to the corresponding rendering nodes. For this monoscopic setup no head tracking or observers are used.

6.2 Runtime Reconfiguration

Switching a layout, as described above, or switching the stereo rendering mode, may involve a different set of resources after the change, including the launch and exit of render client processes. Equalizer solves this through a reconfiguration step at the beginning of each rendering frame. Each resource (channel, window, pipe, node) has an activation count, which is updated when the layout or any other relevant rendering parameter is changed. When a resource is found whose activation count does not match its current start/stopped state, the resource is created or destroyed and configInit or configExit are called accordingly. In the current implementation, a normal configuration initialization or exit, as described in [8], uses the same code path with all used resources transitioning to a running or stopped state, accordingly. Since starting new resources typically requires object mapping and associated data distribution, it is a costly operation.

6.3 Automatic Configuration

Automatic configuration implements the discovery of local and remote resources as well as the creation of typical configurations using the discovered resources at application launch time.

The discovery is implemented in a separate library, hwsd (HardWare Service Discovery), which uses a plugin-based approach to discover GPUs for GLX, AGL or WGL windowing systems, as well as network interfaces on Linux, Mac OS X and Windows. Furthermore, it detects the presence of VirtualGL to allow optimal configuration of remote visualization clusters. The resources can be discovered on the local workstation, and through the help of a simple daemon using the zeroconf protocol, on a set of remote nodes within a visualization cluster. A session identifier may be used to support multiple users on a single cluster.

The Equalizer server uses the hwsd library to discover local and remote resources when an hwsd session name instead of a `.eqc` configuration file is provided. A set of standard decomposition modes is configured, which can be selected through activating the corresponding layout.

This versatile mechanism allows non-experts to configure and profit from multi-GPU workstations and visualization clusters, as well as to provide system administrators with the tools to implement easy to use integration with cluster schedulers.

6.4 Qt Windowing

Qt is a popular window system with application developers. Unfortunately, it imposes a different threading model for window creation and event handling compared to Equalizer. In Equalizer, each GPU rendering thread is independently responsible for creating its windows, receiving the events and eventually dispatching them to the application process' main thread. This design is motivated by the natural threading model of X11 and WGL, and allows simple sequential semantics between OpenGL rendering and event handling. In contrast, Qt requires all windows and each QOpenGLContext to be created from the Qt main thread. An existing Qt window or context may subsequently be moved to a different thread, and events are signalled from the main thread. For Qt windows, Equalizer will internally dispatch and handle the window creation from the render to the main thread, move the created objects back to the render thread, and dispatch Qt signals to the correct render threads.

6.5 Tide Integration

Tide (Tiled interactive display environment) is an improved version of DisplayCluster [23], providing a touch-based, multi-window user interface for high-resolution tiled display walls. Remote applications receive input events and send pixel streams using the Deflect client library. Equalizer includes full support, enabling application-transparent integration with Tide. When a Tide server is configured, all output channels of a view stream in parallel to one window on the wall. In [28], we have shown interactive framerates for a 24 megapixel resolution over a WAN link. Deflect events are translated and injected into the Equalizer event flow, allowing seamless application integration.

6.6 Sequel

Sequel is a simplification layer for Equalizer. It is based on the realization that while fully expressive, the verbatim abstraction layer of nodes, pipes, windows and channels in Equalizer requires significant learning to fully understand and exploit. In reality, a higher abstraction of only Application and Renderer is sufficient for many use cases. In Sequel, the application class drives the configuration, and one renderer instance is created for each (pipe) render thread. They also provide the natural place to store and distribute data. Finally, ViewData provides a convenient way to manage multiple views by storing the camera, model or any other view-specific information.

7 The Collage Network Library

An important part of writing a parallel rendering application is the communication layer between the individual processes. Equalizer relies on the Collage network library for its internal operation. Collage furthermore provides powerful abstractions for writing Equalizer applications, which are introduced in this section. Collage is a separate, standalone library heavily influenced by the requirements of Equalizer. It is used directly when implementing data distribution for parallel rendering applications, and independently by a few research projects.

7.1 Architecture

Collage provides networking functionality of different abstraction layers, gradually providing higher level functionality for the programmer. The main primitives in Collage and their relations are shown in Figure 5 and provide:

Connection A stream-oriented point-to-point communication line. The connections transmit raw data reliably between two endpoints for unicast connections, and between a set of endpoints for multicast connections. For unicast, process-local pipes, TCP and Infiniband RDMA are implemented. For multicast, a reliable, UDP-based protocol is discussed in Section 7.2.

DataI/OStream Abstracts the input and output of C++ data types from or to a set of connections by implementing output stream operators. Uses buffering to aggregate data for network transmission. Performs byte swapping during input if the endianness differs between the remote and local node.

Node and LocalNode The abstraction of a process in the cluster. Nodes communicate with each other using connections. A LocalNode listens on various connections and processes requests for a given process. Received data is wrapped in ICommands and dispatched to command handler methods. A Node is a proxy for a remote LocalNode. The Equalizer Client object is a LocalNode.

Object Provides object-oriented, versioned data distribution of C++ objects between nodes. Objects are registered or mapped on a LocalNode.

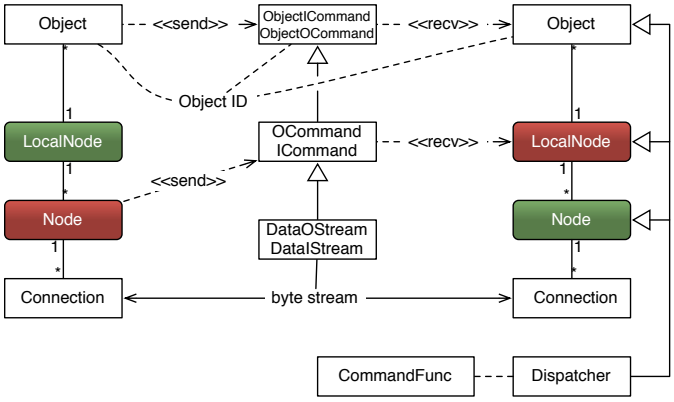


Fig. 5: Communication between two Collage objects

7.2 Reliable Stream Protocol

RSP is an implementation of a reliable multicast protocol over unreliable UDP transport. RSP behaves similarly to TCP; it provides full reliability and ordering of the data, and slow receivers will eventually throttle the sender through a sliding window algorithm. This behavior is needed to guarantee delivery of data in all situations. Pragmatic generic multicast (PGM [16]) provides full ordering, but slow clients will disconnect from the multicast session instead of throttling the send rate.

RSP combines various established algorithms [1], [15] for multicast in an open source implementation capable of delivering wire speed transmission rates on high-speed LAN interfaces. In the following we will outline the RSP protocol and implementation as well as motivate the design decisions. Any defaults given below are for Linux or OS X, the Windows UDP stack requires different default values which can be found in the implementation.

Our RSP implementation uses a separate protocol thread for each RSP group, which handles all reads and writes on the multicast socket. It implements the protocol handling and communicates with the application threads through thread-safe queues. The queues contain datagrams of the application byte stream, prefixed by a header of at most eight bytes. Each connection has a configurable number of buffers (1024 by default) of a configurable MTU (1470 bytes default), which are either free or in transmission.

Handling a smooth packet flow is critical for performance. RSP uses active flow control to advance the byte stream buffered by the implementation. Each incoming connection actively acknowledges every n (17 by default) packets fully received. The incoming connections offset this acknowledgment by their connection identifier to avoid bursts of acks. Any missed datagram is actively nack'ed as soon as detected. Write connections continuously retransmit packets for nack datagrams, and advance their window upon reception of all acks from the group. The writer will explicitly request an ack or nack when it runs out of empty buffers or finishes its write queue. Nack datagrams may contain multiple ranges of missed datagrams, which is motivated by the observation that UDP implementations often drop multiple contiguous packets.

Congestion control is necessary to optimize bandwidth usage. While TCP uses the well-known additive increase, multiplicative decrease algorithm, we have chosen a more aggressive congestion control algorithm of additive increase and additive decrease. This has proven experimentally to be more optimal: UDP is often rate-limited by switches; that is, packets are discarded regularly and not exceptionally. Only slowly backing of the current send rate helps to stay close to this limit. Furthermore, our RSP traffic is limited to the local subnet, making cooperation between multiple data stream less of an issue. Send rate limiting uses a bucket algorithm, where over time the bucket fills with send credits, from which sends are substracted. If there are no available credits, the sender sleeps until sufficient credits are available.

7.3 Distributed, Versioned Objects

Adapting an existing application for parallel rendering requires the synchronization of application data across the processes in the parallel rendering setup. Existing parallel rendering frameworks address this often poorly, at best they rely on MPI to distribute data. Real-world, interactive visualization applications are typically written in C++ and have complex data models and class hierarchies to represent their application state. As outlined in [8], the parallel rendering code in an Equalizer application only needs access to the data needed for rendering, as all application logic is centralized in the application main thread. We have encountered two main approaches to address this distribution: Using a shared filesystem for static data, or using data distribution for static and dynamic data. Distributed objects are not required to build Equalizer applications. While most developers choose to use this abstraction for convenience, we have seen applications using other means for data distribution, e.g., MPI.

7.3.1 Programming Interface

Distributed objects in Collage provide powerful, object-oriented data distribution for C++ objects. They facilitate the implementation of data distribution in a cluster environment. Distributed objects are created by subclassing from co::Serializable or co::Object. The application programmer implements serialization

and deserialization. Distributed objects can be static (immutable) or dynamic. Objects have a universally unique identifier (UUID) as cluster-wide address. A master-slave model is used to establish mapping and data synchronization across processes. Typically, the application main loop registers a master instance and communicates the UUID to the render clients, which map their instance to the given identifier. The following object types are available:

Static The object is not versioned nor buffered. The instance data is serialized whenever a new slave instance is mapped. No additional data is stored.

Instance The object is versioned and buffered. The instance and delta data are identical; that is, only instance data is serialized. Previous instance data is saved to be able to map old versions.

Delta The object is versioned and buffered. The delta data is typically smaller than the instance data. The delta data is transmitted to slave instances for synchronization. Previous instance and delta data is saved to be able to map and sync old versions.

Unbuffered The object is versioned and unbuffered. No data is stored, and no previous versions can be mapped.

Serialization is facilitated using output or input streams, which abstract the data transmission and are used like a std::stream. The data streams implement efficient buffering and compression, and automatically select the best connection for data transport. Custom data type serializers can be implemented by providing the appropriate serialization functions. No pointers should be directly transmitted through the data streams. For pointers, the corresponding object is typically a distributed object as well, and its UUID and version are transmitted in place of a pointer.

Dynamic objects are versioned, and on commit the delta data from the previous version is sent, if available using multicast, to all mapped slave instances. The data is queued on the remote node, and is applied when the application calls sync to synchronize the object to a new version. The sync method might block if a version has not yet been committed or is still in transmission. All versioned objects have the following characteristics:

- The master instance of the object generates new versions for all slaves. These versions are continuous. It is possible to commit on slave instances, but special care has to be taken to handle possible conflicts.
- Slave instance versions can only be advanced; that is, sync(version) with a version smaller than the current version will fail.
- Newly mapped slave instances are mapped to the oldest available version by default, or to the version specified when calling mapObject.

The Collage Serializable implements one convenient usage pattern for object data distribution. The co::Serializable data distribution is based on the concept of dirty bits, allowing inheritance with data distribution. Dirty bits form a 64-bit mask which marks the parts of the object to be distributed during the next commit. For serialization, the application developer implements serialize or deserialize, which are called with the bit mask specifying which data has to be transmitted or received. During a commit or sync, the current dirty bits are given, whereas during object mapping all dirty bits are passed to the serialization methods.

Blocking commits allow to limit the number of outstanding, queued versions on the slave nodes. A token-based protocol will block the commit on the master instance if too many unsynchronized versions exist.

7.3.2 Optimizations

The API presented in the previous section provides sufficient abstraction to implement various optimizations for faster mapping and synchronization of data: compression, chunking, caching, preloading and multicast. The results section evaluates some of these optimizations.

The most obvious one is compression. Recently, many new compression algorithms have been developed which exploit modern CPU architectures and deliver compression rates well above one gigabyte per second. Collage uses the Pression library [17], which provides a unified interface for a number of compression libraries, such as FastLZ [22], Snappy [31] and ZStandard [12]. It also contains a custom, virtually zero-cost RLE compressor. Pression parallelizes the compression and decompression using data decomposition. This compression is generic, and implemented transparently for the application. Applications can also use data-specific compression.

The data streaming interface implements chunking, which pipelines the serialization code with the network transmission. After a configurable number of bytes has been serialized to the internal buffer, it is transmitted and serialization continues. This is used both for the initial mapping data and for commit data.

Caching retains instance data of objects in a client-side cache, and reuses this data to accelerate mapping of objects. The instance cache is either filled by "snooping" on multicast transmissions or by an explicit preloading when the master objects are registered. The preloading sends instance data of recently registered master objects to all connected nodes, while the corresponding node is idle. These nodes simply enter the received data to their cache. Preloading uses multicast when available.

Due to the master-slave model of data distribution, multicast is used to optimize the transmission time of data. If the contributing nodes share a multicast session, and more than one slave instance is mapped, Collage automatically uses the multicast connection to send the new version information.

7.4 Barriers, Queues and Object Maps

Collage implements a few generic distributed objects which are used by Equalizer and other applications. A barrier is a distributed barrier primitive used for software swap synchronization in Equalizer (Section 6.1). Its implementation follows a simple master-slave approach, which has shown to by sufficient for this use case. Queues are distributed, single producer, multiple consumer FIFO queues. To hide network latencies, consumers prefetch items into a local queue. Queues are used for tile and chunk compounds (Section 4.1.2).

The object map facilitates distribution and synchronization of a collection of distributed objects. Master versions can be registered on a central node, e.g., the application node in Equalizer. Consumers, e.g., Equalizer render clients, can selectively map the objects they are interested in. Committing the object map will commit all registered objects and sync their new version to the slaves. Syncing the map on the slaves will synchronize all mapped instances to the new version recorded in the object map. This effective design allows data distribution with minimal application logic. It is used by Sequel (Section 6.6) and other Collage applications.

8 APPLICATIONS

In this section, we present some major applications built using Equalizer, and show how they interact with the framework to solve complex parallel rendering problems.

8.1 Livre

Livre (Large-scale Interactive Volume Rendering Engine) is a GPU ray-casting based parallel 4D volume renderer, implementing state-of-the-art view-dependent level-of-detail rendering (LOD) and out-of-core data management [10]. Hierarchical and out-of-core LOD data management is supported by an implicit volume octree, accessed asynchronously by the renderer from a data source on a shared file system. Different data sources providing an octree conform access to RAW or compressed as well as to implicitly generated volume data (e.g. such as from event simulations or surface meshes) can be used.

High-level state information, e.g., camera position and rendering settings, is shared in Livre through Collage objects between the parallel applications and rendering threads. Sort-first decomposition is efficiently supported through octree traversal and culling both for scalability as well as for driving large-scale tiled display walls.

8.2 RTT Deltagen

RTT Deltagen (Figure 4, now Dassault 3D Excite) is a commercial application for interactive, high quality rendering of CAD data. The RTT Scale module, delivering multi-GPU and distributed execution, is based on Equalizer and Collage, and has driven many of the aforementioned features.

RTT Scale uses a master-slave execution mode, where a single running Deltagen instance can go into "Scale mode" at any time by launching an Equalizer configuration. Consequently, the whole internal representation needed for rendering is based on a Collage-based data distribution. The rendering clients are separate, smaller applications which will map their scenes during startup. At runtime, any change performed in the main application is committed as a delta at the beginning of the next frame, following a design pattern similar to the Collage Serializable (Section 7.3.1). Multicast (Section 7.2) is used to keep data distribution times during session launch reasonable for larger cluster sizes (tens to hundreds of nodes).

RTT Scale is used for a wide variety of use cases. In virtual reality, the application is used for virtual prototyping and design reviews in front of high-resolution display walls and CAVEs, as well as for virtual prototyping of human-machine interactions using CAVEs and HMDs (Figure 1(b)). For scalability, sort-first and tile compounds are used to achieve fast, high-quality rendering, primarily for interactive raytracing, both based on CPUs and GPUs. For CPU-based raytracing, often Linux-based rendering clients are used with a Windows-based application node.

8.3 RTNeuron

RTNeuron [20] is a scalable real-time rendering tool for the visualisation of neuronal simulations based on cable models (Figure 1 (a)). It is based on OpenSceneGraph for data management and Equalizer for parallel rendering, and focuses not only on fast rendering times, but also on fast loading times with no offline preprocessing. It provides level of detail (LOD) rendering, high quality anti-aliasing based on jittered frusta and accumulation during still views, interactive modification of the visual representation of neurons on a per-neuron basis (full neuron vs. soma only, branch pruning depending on the branch level, ...). RTNeuron implements both sort-first and sort-last rendering with order independent transparency.

8.4 RASTeR

RASTeR [4] is an out-of-core and view-dependent real-time multiresolution terrain rendering approach using a patch-based restricted quadtree triangulation. For load-balanced parallel rendering [19] it exploits fast hierarchical view-frustum culling of the level-of-detail (LOD) quadtree for sort-first decomposition, and uniform distribution of the visible LOD triangle patches for sort-last decomposition. The latter is enabled by a fast traversal of the patch-based restricted quadtree triangulation hierarchy which results in a list of selected LOD nodes, constituting a view-dependent cut or *front of activated nodes* through the LOD hierarchy. Assigning and distributing equally sized segments of this active LOD front to the concurrent rendering threads results in a near-optimal sort-last decomposition for each frame.

8.5 Bino

Bino is a stereoscopic 3D video player capable of running on very large display systems. Originally written for the immersive semi-cylindrical projection system at the University of Siegen, it has been used in many installations thanks to its flexibility of configuration. Bino decodes the video on each Equalizer rendering process, and only synchronizes the time step globally, therefore providing a scalable solution to video playback.

8.6 Omegalib

Omegalib [13] is a software framework built on top of Equalizer that facilitates application development for hybrid reality environments such as the Cave 2. Hybrid reality enviroments aim to create a seamless 2D/3D environment that supports both information-rich analysis (traditionally done on tiled display wall) as well as virtual reality simulation exploration (traditionally done in VR systems) at a resolution matching human visual acuity. Omegalib supports dynamic reconfigurability of the display environment, so that areas of the display can be interactively allocated to 2D or 3D workspaces as needed. It makes it possible to have multiple immersive applications running on a cluster-controlled display system, have different input sources dynamically routed to applications, and have rendering results optionally redirected to a distributed compositing manager. Omegalib supports pluggable front-ends, to simplify the integration of third-party libraries like OpenGL, OpenSceneGraph, and the Visualization Toolkit (VTK).

9 EXPERIMENTAL RESULTS

This section presents new experiments, complementing the results of previous publications [7], [8], [9], [11], [20], [25], [28], [32]. The first part summarizes rendering performance over all decomposition modes with a few representative workloads. The second part analyses data distribution performance, in particular how the optimizations in Collage perform in realistic scenarios.

9.1 Decomposition Modes

We conducted new performance benchmarks for various decomposition modes on a cluster using hexacore Intel Xeon E5-2620v3 CPUs (2.4 GHz), nVidia GTX 970 GPUs with 4 GB VRAM each, 16 GB main memory per node, 4 GBit/s Ethernet, and QDR Infiniband. GCC 4.8 has been used with CMake 3.7 release mode settings to compile the software stack.

We tested the decomposition modes with both polygonal data and volume data (Figure 6 (middle and left)), using test scenes that allowed to adapt the rendering load the system has to cope with. In both cases the scene is comprised of two rows of instantiated, identical models with 30 models in total. Rendering was performed at an output resolution of 2560×1440. The camera is initially placed in the center of the scene, between the two rows, rendering only half of the model instances. It is then moved backward over the duration of 800 frames, steadily increasing the rendering load by revealing more models, until all 30 instances are visible.

We investigated the scalability of individual decomposition modes by running the same experiment using a varying number of render nodes (2-9) and one dedicated application/display node. We subsequently summed up the duration of all rendered frames for each run (Figure 8).

For sort-first and sort-last rendering we present static and load-balanced task decomposition. For readability, we only present the results of the equalizer (load or tree) providing the better performance for each application. Unsurprisingly, static decompositions perform worse over load-balanced compounds. Sort-first polygon rendering exhibits oscillations in performance as nodes are added to the task, due to unfavorable assignment of a tile with a high work load on odd node counts. Static sort-last volume rendering has a similar oscillation behaviour, as ranges of scene geometry tend to also get unfavorably assigned under such conditions. Sort-first performs better for volume rendering since it is easier to load balance than in our polygonal renderer due to the predictable per-fragment cost. The polygonal renderer performs better in sort-last rendering, since sort-first is harder to load balance and observes inefficencies when geometry is intersected by a load split and has to be rendered by both resources.

The simpler tree_equalizer outperforms in almost all cases the load-grid-driven load_equalizer, except for sort-first volume rendering where the load in the region of interest is relatively uniform. This counterintuitive result seems to again confirm that simple algorithms often outperform theoretically better, but more complex implementations. On the other hand, the tile_equalizer often outperforms tree_equalizer. This suggests that the underlying implicit load balancing can be superior to the explicit methods of load_equalizer and tree_equalizer in high load situations, where the additional overhead of tile generation and distribution is more justified. The relatively simple nature of our benchmark application's rendering algorithms is also favoring work packages, since they have a near-zero static overhead per rendering pass.

Finally, we also provide scalability results for pixel compounds. While naturally load-balanced, pixel compounds only scale fill rate and not geometry processing. Consequently, pixel compounds provide better performance for volume rendering, and a predictable scaling behaviour for both.

For volume rendering we also measured the performance of decomposition modes under heterogeneous load, which was easily achievable by varying the number of volume samples used for each fragment (1-7) while rendering. This allowed for a consistent linear scaling of rendering load, which was randomly varied (Figure 9) either per frame or per node. Such a linear scaling of load per node corresponds to a scaling of resources, e.g., doubling the rendering load on a specific node corresponds to halving its available rendering resources. To the system this node would then contribute the value 0.5 in terms of *normalized compute resources*, as illustrated by Figure 9 (left).

This figure gives an impression of how individual modes perform on heterogeneous systems. In this case the tree equalizer performs best (Figure 9 (left)), as it allows us to a priori define how much *usage* it should make of individual nodes, i.e., bias the allocation of rendering time in accordance with the (simulated) compute resources. Figure 9 (right), on the other hand, illustrates how the tested decomposition modes perform on a system where compute resources fluctuate randomly every frame, as can arguably be the case for shared rendering nodes in virtualized enviroments. For this scenario tile_equalizer seems best suited, as it performs load balancing implicitly and does not assume coherence of available resources between frames. The simpler tree equalizer also outperforms the load_equalizer in this experiment.

9.2 Object Distribution

The data distribution benchmarks have been performed on a cluster using dual processor Intel Xeon X5690 CPUs (3.47 GHz), 24 GB main memory per node, 10 GBit/s Ethernet and QDR Infiniband. Intel ICC 2017 has been used with CMake 3.2 release mode settings to compile the software stack. To benchmark the data distribution we used two datasets: The David statue at 2 mm resolution (as in Figure 6 (middle), but in 2 mm resolution) and 3D volumes of spike frequencies of an electrical simulation of three million neurons (Figure 6 (right)).

The PLY file is converted into a k-d tree for fast view frustum culling and rendering, and the resulting data structure is serialized in binary form for data transmission. The spike frequency volumes aggregate the number of spikes which happened within a given voxel over a given time. The absolute spike count is renormalized to an unsigned byte value during creation. Higher densities in the volume represent higher spiking activity in the voxel.

9.2.1 Data Compression Engines

A critical piece for data distribution performance are the characteristics of the data compression algorithm. Our microbenchmark compresses a set of binary files, precalculating the speed and compression ratio of the various engines. Figure 7 shows the compression and decompression speed in gigabyte per second as well as the size of the compressed data relative to the uncompressed data. The ZSTDx engines use the ZStandard compression library at compression level x. The measurements were performed on a single, isolated node.

RLE compression has a very low overhead but merely removes "blank space" in the data. The Snappy compression, used as default in Collage, achieves the same compression ratio as the LZ variants at a much higher speed. The ZStandard compressor has roughly the same speed as the LZ variants at the lowest compression level, but provides significantly better compression. At higher compression levels it can improve the compression ratio slightly, but at a high cost for the compression speed.

The compression ratio for the models used in the following section deviate from this averaged distribution. Figure 10 shows the compression ratios for the triangle and volume data.

Fig. 6: Benchmark data: Flower alley with 30 volume models of 1024^3 unsigned bytes (1 GB) each (left); David alley with 30 statues of 56 M triangles (988 MB) each (middle); Volumes used for object distribution benchmarks (right): spike frequencies of a three million neuron electrical simulation at $512 \times 437 \times 240$ unsigned byte (51 MB) and an MicroCT scan of a beechnut at $1024 \times 1024 \times 1546$ unsigned short (3 GB) resolution

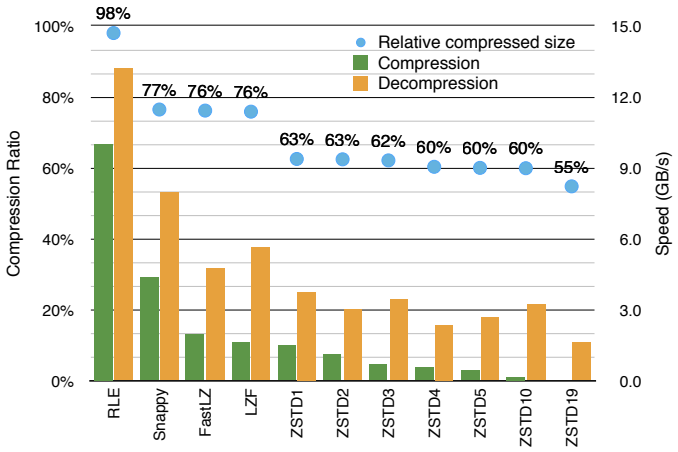


Fig. 7: Data compression for generic binary data

The PLY data is little compressible, the default compressor achieves a 10% reduction. This is due to a high entropy in the data and the dominant use of floating point values. Overall, the profile is similar to the generic benchmark, at a smaller compression rate.

The volume data on the other hand is sparsely populated and using integer (byte and short) values, which is easier to compress. The naive RLE implementation already achieves a good compression rate, showing that the smaller volume contains at most 28% empty space and the bigger volume at most 43%. Snappy and ZStandard can reduce the spike data much further, reducing the data to a few megabytes. Surprisingly, the beechnut data set does not yield significantly higher compression with the modern Snappy and ZStandard libraries.

9.2.2 Model Distribution and Update

In this section we analyse how data distribution and synchronization performs in real-world applications. We extracted the existing data distribution code from a mesh renderer (eqPly) and a volume renderer (Livre) into a benchmark application to measure the time to initially map all the objects on the render client nodes, and to perform a commit-sync of the full data set after mapping has been established. All figures observe a noticable measurement jitter due to other services running on the cluster. The details of the benchmark algorithm can be found in the implementation[1].

We used the same data sets as in the previous section, and ran the benchmark on up to eight physical nodes, that is, after eight processes nodes start to run two processes per node, which share CPU, memory and network interface bandwidth.

Object mapping is measured using the following settings: **none** distributes the raw, uncompressed, and unbuffered data, **compression** uses the Snappy compressor to distribute unbuffered data, **buffered** reuses uncompressed, serialized data for mappings from multiple nodes, and **compression buffered** reused the compressed buffer for multiple nodes. Unbuffered operations need to reserialize, and potentially recompress, the master object data for each slave node. Each slave instance needs to deserialize and decompress the data.

During data synchronization, the master commits the object data to all mapped slave instances simultaneously. This is a "push" operation, whereas the mapping is a slave-triggered "pull" operation. During commit, the buffers only have to be serialized and compressed once, and can then be sent directly to all mapped slave nodes. Slave nodes queue this data and consume it during synchronization. In contrast, object mapping needs to wait for each slave node to request the mapping, and then may need to reserialize and compress the object data. We test the time to commit and sync the data using different compression engines.

The David statue at 2 mm resolution is organized in a k-d tree for rendering. Each node is a separate distributed object, which has two child node objects. A total of 1023 objects are distributed and synchronized. Figure 11 shows the distribution times for this data set. Due to limited compressibility of the data, the results are relatively similar. Compressing the data repeatedly for each client leads to decreased performance, since the compression overhead cannot be amortized by the decreased transmission time. Buffering data slightly improves performance by reducing the CPU and copy overhead. Combining compression and buffering leads to the best performance, although only by about 10%.

During synchronization, data is pushed from the master process to all mapped slaves using a unicast connection to each slave. While the results in the Figure 11 (middle) are relatively close to each other, we can still observe how the tradeoff between compression ratio and speed influences overall performance. Better, slower compression algorithms lead to improved overall performance when amortized over many send operations.

The volume data sets are distributed in a single object, serializing the raw volume buffer. The Spike volume data set has a significant compression ratio, which is reflected by the results in Figure 12. Compression for this data is beneficial for transmitting data over a 10 Gb/s link even for a single slave process. Buffering has little benefit since the serialization of volume data is trivial. Buffered compression makes a significant difference, since the

1. https://github.com/Eyescale/Equalizer/tree/paper2018/tools/eqObjectBench

compression cost can be amortized over n nodes, reaching raw data transmission rates of 3.7 GB/s with the default Snappy compressor and at best 4.4 GB/s with ZStandard at level 1.

The distribution of the beechnut data set also behaves as expected (Figure 13). Due to the larger object size, uncompressed transmission is slightly faster compared to the Spike data set at 700 MB/s, and compressed transmission does not improve the mapping performance, likely due to increased memory pressure caused by the large data size. The comparison of the various compression engines is consistent with the benchmarks in Figure 10; RLE, Snappy and the LZ variants are very close to each other, and ZSTD1 can provide better performance after four nodes due to the better compression ratio.

Finally, we compare data distribution speed using different protocols. In this benchmark, data synchronization time of the Spike volume data set is measured, as in Figure 12 (middle). Buffering is enabled, and compression is disabled to focus on the raw network performance. Figure 14 shows the performance using various protocols. TCP over the faster InfiniBand link outperforms the cheaper ten gigabit ethernet link by more than a factor of two. Unexpectedly, the native RDMA connection performs worse, even though it outperforms IPoIB in a simple peer-to-peer connection benchmark. This needs further investigation, but we suspect the abstraction of a byte stream connection chosen by Collage is not well suited for remote DMA semantics; that is, one needs to design the network API around zero-copy semantics with managed memory for modern high-speed transports. Both Infiniband connections show significant measurement jitter.

RSP multicast performs as expected. Collage starts using multicast to commit new object versions when two or more clients are mapped, since the transmission to a single client is faster using unicast. RSP consistently outperforms unicast on the same physical interface and shows good scaling behavior (2.5 times slower on 16 vs 2 clients on ethernet, 1.8 times slower on InfiniBand). The scaling is significantly better when only one process per node is used (Figure 14, middle: 30% slower on ethernet, nearly flat on InfiniBand). The increased transmission time with multiple clients is caused by a higher probability of packet loss, which increases significantly when using more than one process per node. Figure 14 (right) plots the number of retransmissions divided by the number of datagrams. Infiniband outperforms ethernet slightly, but is largely limited by the RSP implementation throughput of preparing and queueing the datagrams to and from the protocol thread, which we observed in profiling.

10 Discussion and Conclusion

We have presented a significantly improved generic parallel rendering system over the original publication [8]. While the original publication motivated the system design, this publication describes a feature-rich, mature implementation capable of supporting a wide variety of use cases. We doubled the support for scalable rendering modes, many of which are presented here for the first time. We present new runtime adaptations for better load balance and performance, describe how common optimizations are integrated into the system, making Equalizer the most generically available scalable rendering system.

Furthermore, we present many new features needed in parallel rendering applications, from advanced Virtual Reality support to advanced display system setup for 2D/3D integration, autoconfiguration and runtime reconfiguration, and an advanced network data synchronization library tailored to parallel rendering applications. We highlight a few commercial and research applications underlining the generic and versatile system implementation.

With respect to the feature set implemented, we believe that Equalizer now covers almost any scenario within its scope. For future work, we would like to integrate new research for better scalability, new network implementations in particular for modern zero-copy RDMA based transports, as well as extending the Sequel abstraction layer for ease of use.

Acknowledgments

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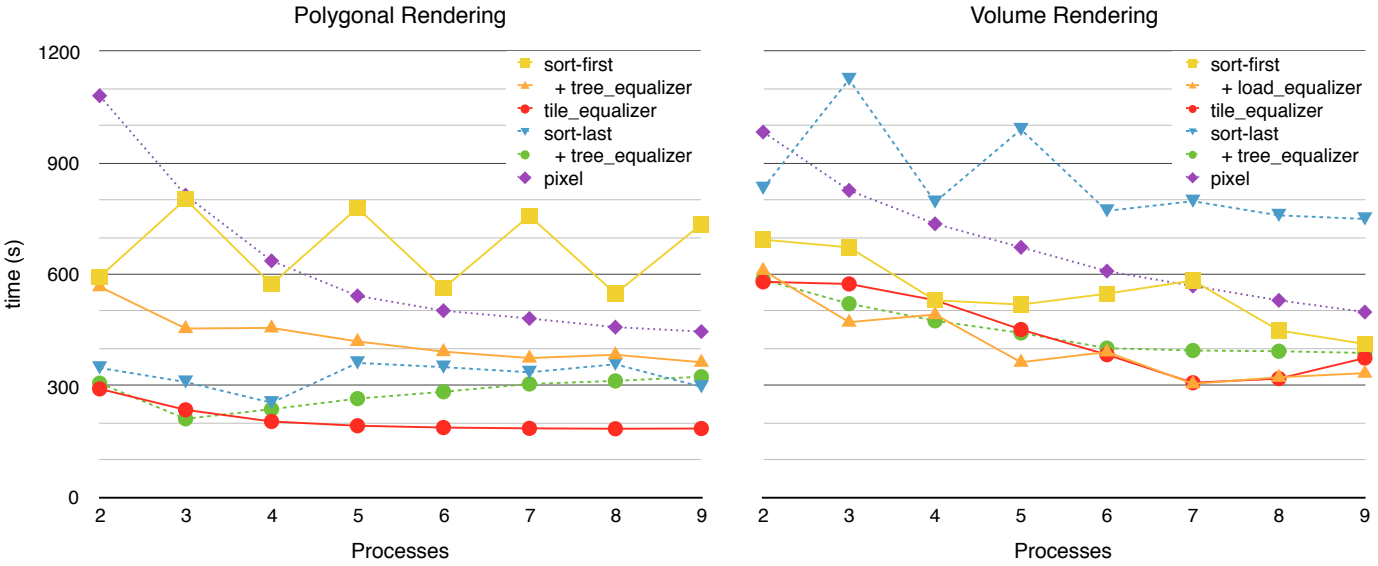

Fig. 8: Compound scalability for polygonal and volume data

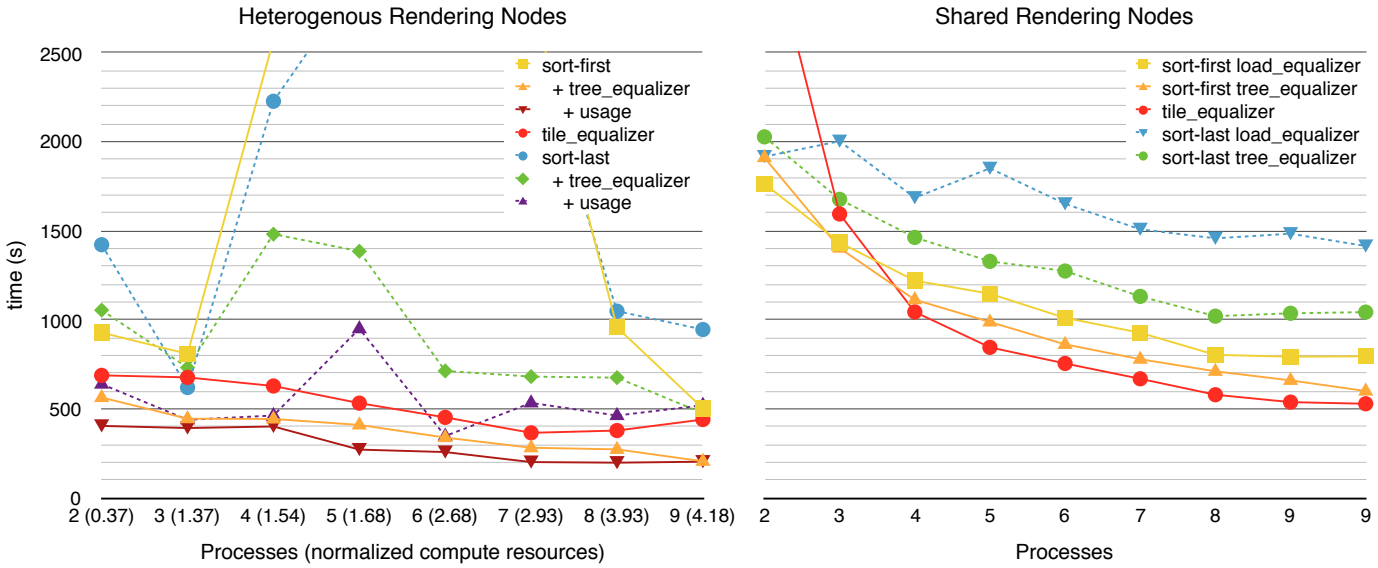

Fig. 9: Scalability with heterogenous rendering resources

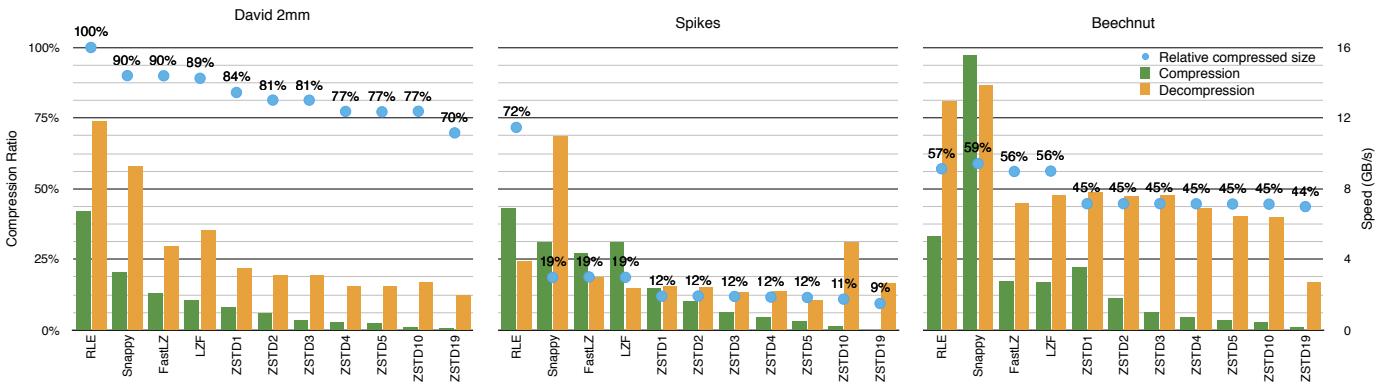

Fig. 10: Data compression for PLY data (left, David statue 2 mm) and raw volumes shown in Figure 6 (right)

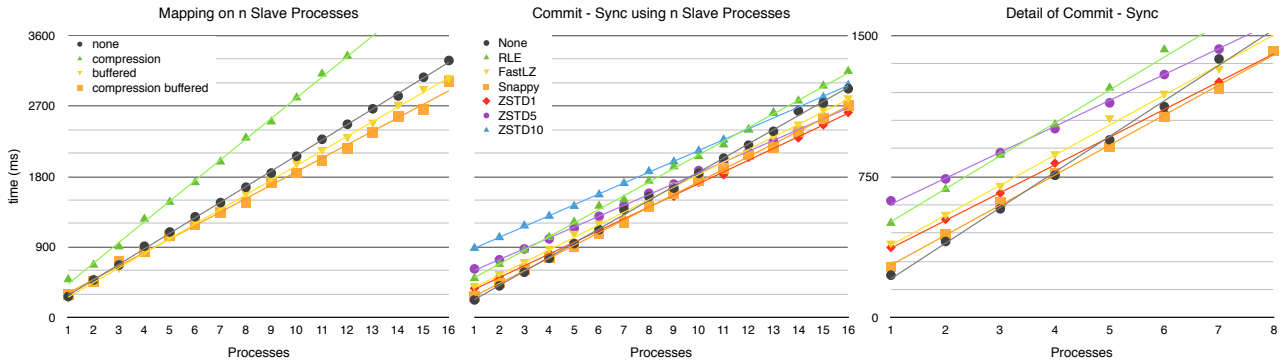

Fig. 11: Object mapping (left) and data synchronization time (middle, detail view right) for the David 2 mm data set

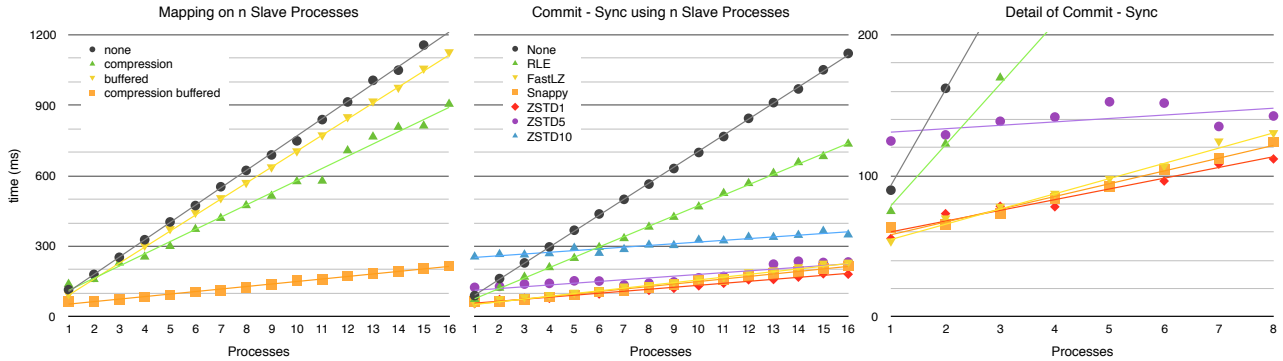

Fig. 12: Object mapping (left) and data synchronization time (middle, detail view right) for the Spike data set in Figure 6 (right)

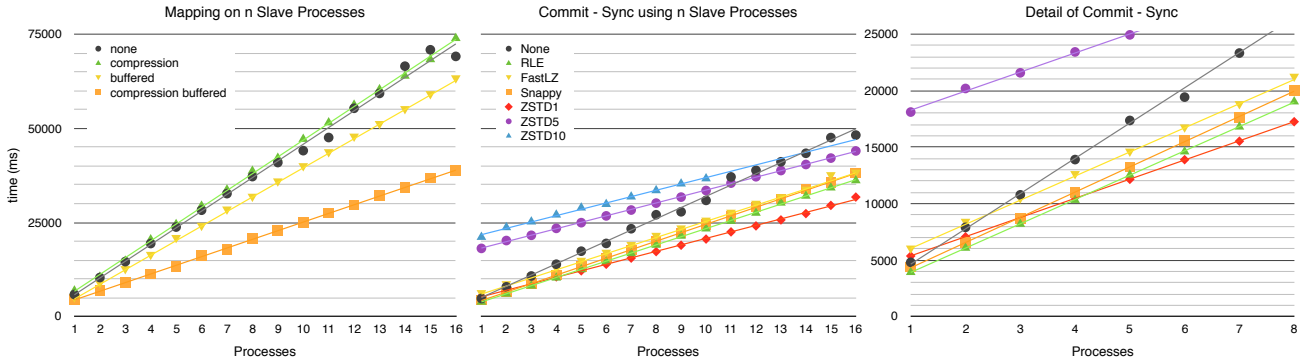

Fig. 13: Object mapping (left) and data synchronization time (middle, detail view right) for the beechnut data set in Figure 6 (right)

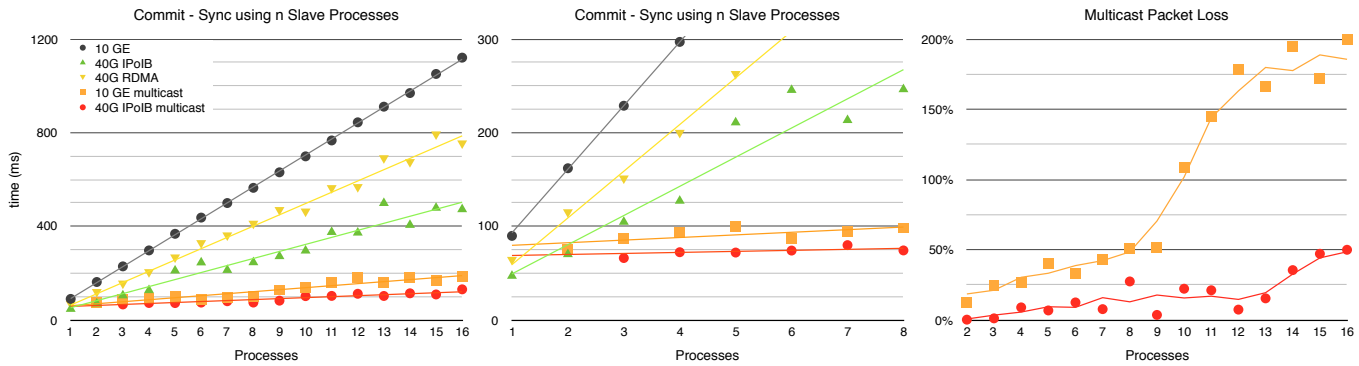

Fig. 14: Object synchronization using different network transports