Outatime: Using Speculation to Enable Low-Latency Continuous Interaction for Mobile Cloud Gaming

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Background: Cloud Gaming

- Processing and rendering done on cloud
- Client sends inputs, receives rendered images
- Benefits
  - Better graphics – use server’s processing hardware
  - Easy to develop – no compatibility issues

The Problem

- Lacks *real-time interactivity*
  - High latency sensitivity affects gameplay
  - Buffering impossible due to changing user input

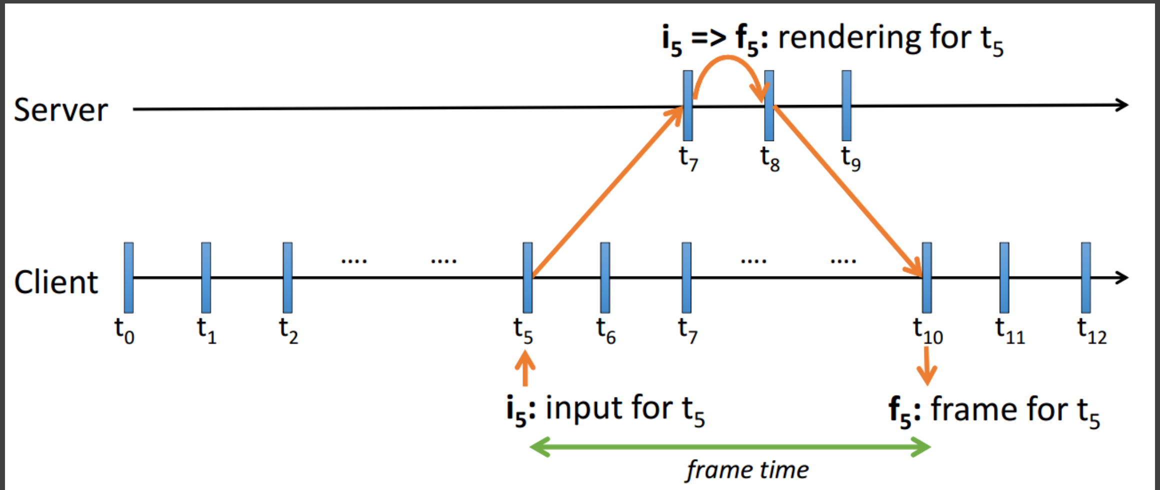


Fig. 1 (a) – Standard Cloud Gaming: Frame time depends on net latency

Solution

- Speculate frames until next response
- Challenges – dynamism and sensitivity

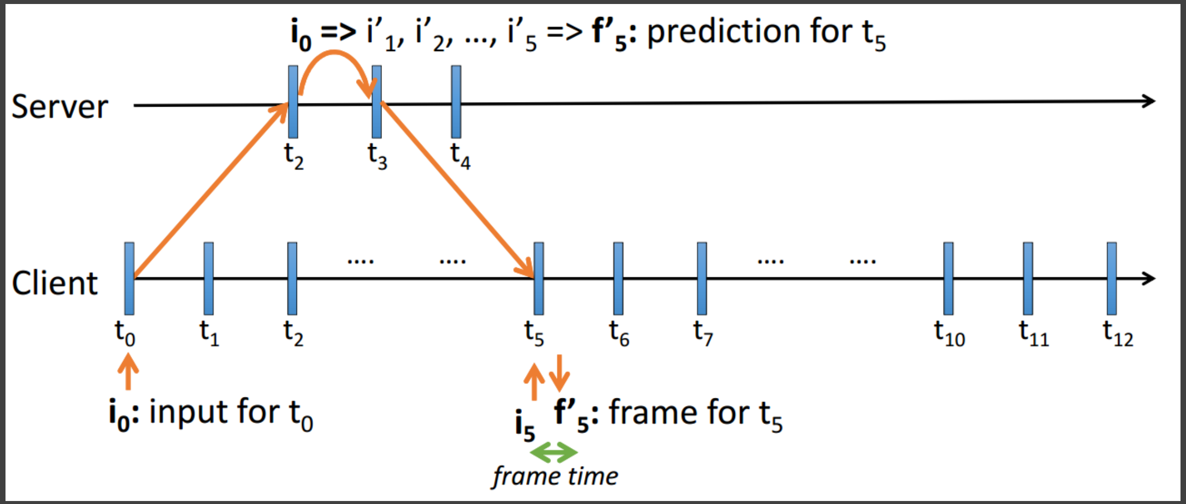


Fig. 1 (b) – Outatime: Frame time is negligible

Outatime Architecture

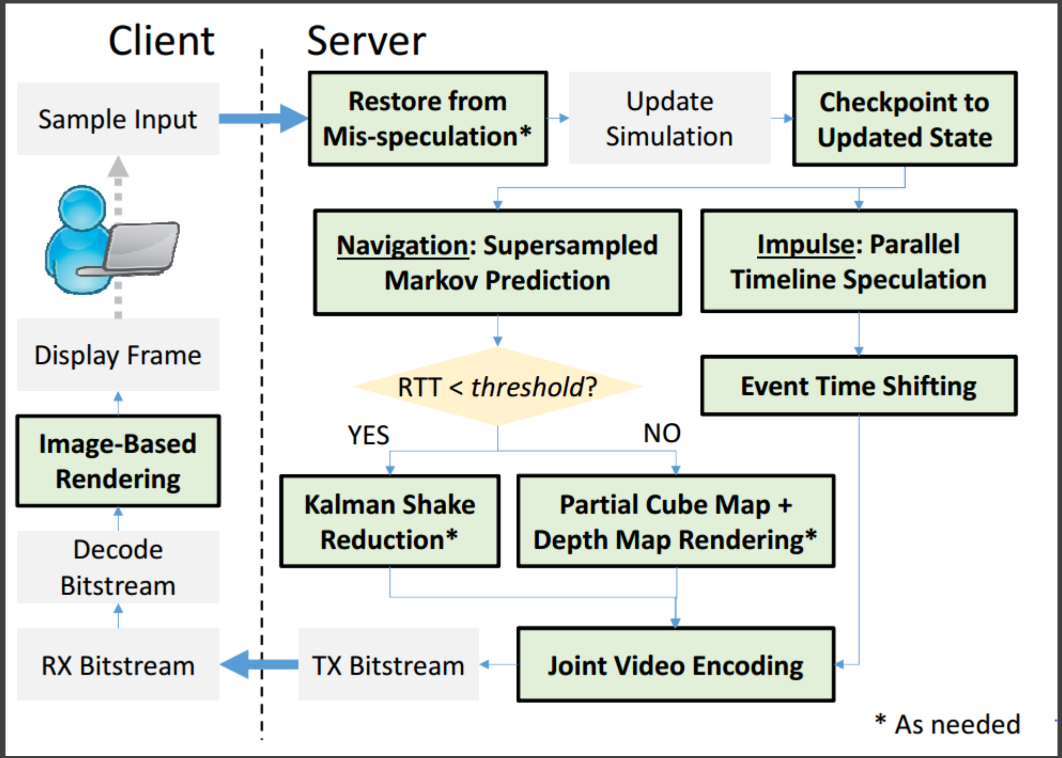


Fig. 2: Outatime Architecture

Speculation for Navigation

- Create discrete time Markov Chain
  - Define input $N_t = \{\delta_{x,t}, \delta_{y,t}, \delta_{z,t}, \theta_{x,t}, \theta_{y,t}, \theta_{z,t}\}$
  - Given input n_t, find most likely input for next frame $\widehat{N}_{t+1}$
  - For RTT λ:

$$\widehat{N}_{t+\lambda} = argmax\left[p(N_{t+1}|N_t = n_t) * \prod_{i=1}^{\lambda-1} p(N_{t+i+1}|N_{t+i})\right]$$

  - Also track error estimate

Speculation for Navigation

- Supersampling – Collect data as fast as input device allows
  - Improves accuracy
  - Reduces sampling noise
- Prediction accuracy improves over 5 min. of samples
- Use training data of other players
  - Characteristics depend on skill level

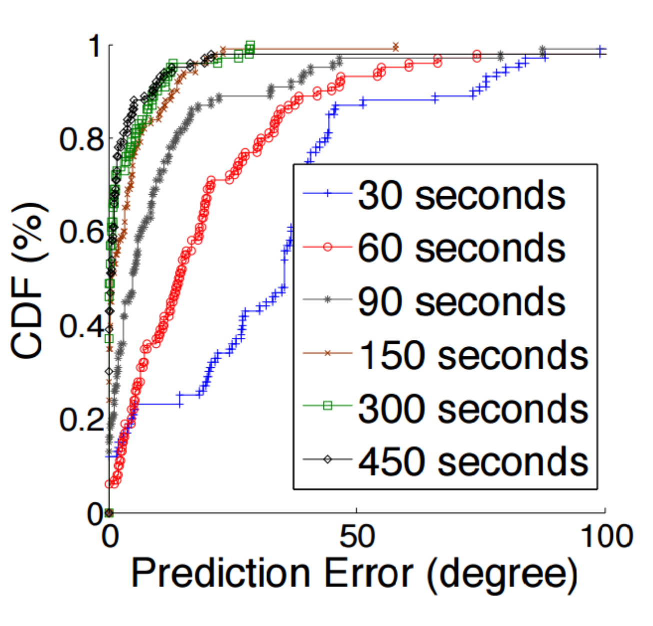


Fig. 5 – Error distribution for different training periods

Speculation for Navigation

- Video Shake
  - Caused by small prediction errors at low-latency
  - Fixed using Kalman Filtering

- Kalman Filter
  - Emphasizes measured values for low RTT (< 40ms.)
  - Emphasizes predicted values for high RTT (> 40ms.)

Misprediction Compensation

- Image-based Rendering
  - Transform rendered prediction to be more accurate
- Clipped Cube Map
  - Render areas surrounding frame in case they are needed
  - Limit size based on expected error values

Clipped Cube Map

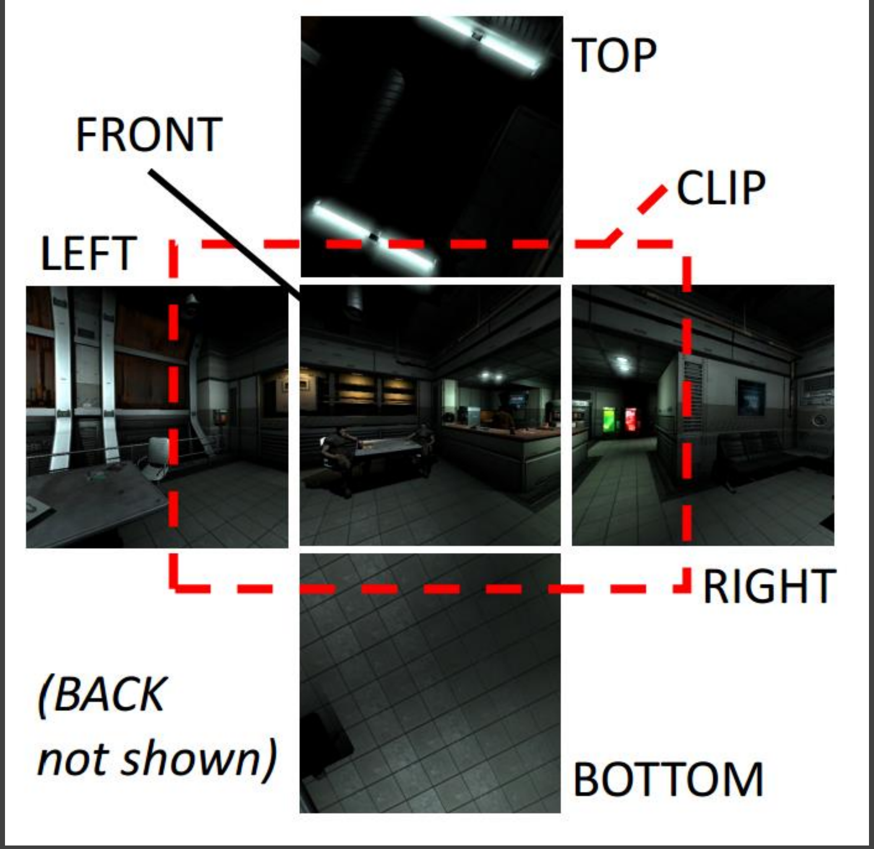


Fig. 7 – Cube Map Example

Image-based Rendering (IBR)

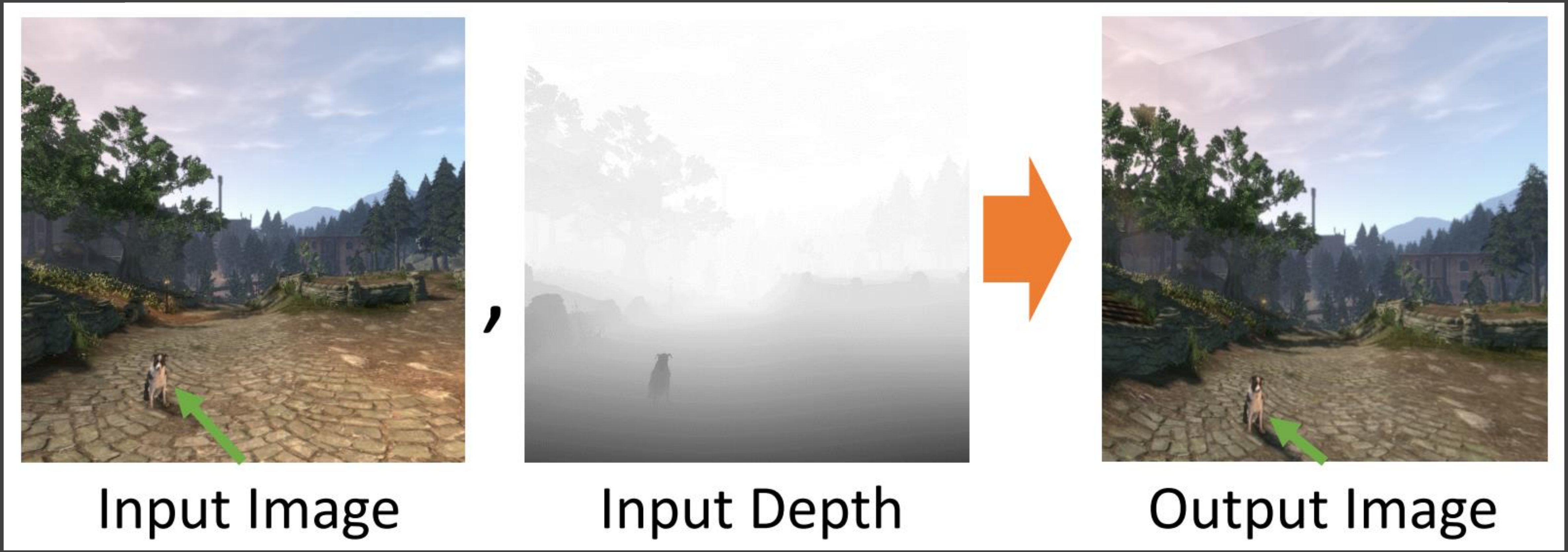


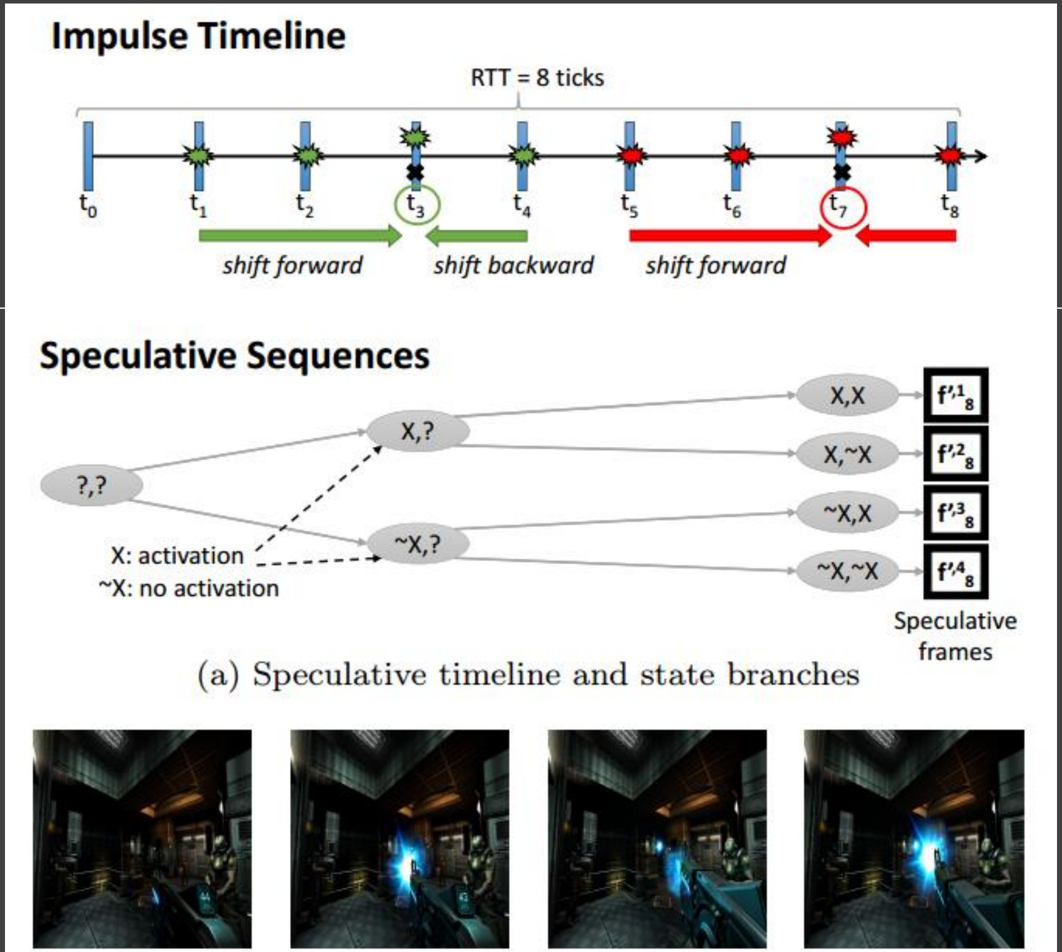
Figure 6 – Image-based Rendering in Fable 3

Speculation for Impulse Events

- Much harder to predict
- Solution: speculate different possibilities in parallel
- Create speculative input sequence
- As RTT increases, speculative sequence space grows exponentially
- Two methods to decrease speculative sequence size
  - Subsampling
  - Time-Shifting

Subsampling and Time-Shifting

- Subsampling
  - Sample inputs at a period $\sigma > 1$ clock tick
  - Reduces state space to $2^{\frac{\lambda}{\sigma}}$
  - On its own, likely to miss samples
- Time-shifting
  - Shift every input activation to occur on the nearest subsample
  - Solves problem of subsampling
  - Can shift inputs backwards since state is speculative



(a) Speculative timeline and state branches

(b) ∼X, ∼X (c) ∼X, X (d) X,∼X (e) X,X

Figure 10: Subsampling and time-shifting impulse events allows the server to bound speculation to a maximum of four sequences even for RTT= 256ms. Screenshots (b) – (e) show speculative frames corresponding to four activation sequences of weapon fire and no fire.

Speculation for Impulse Events

- Not all inputs are binary
  - Alternate firing for a weapon
- State space grows quickly (eg. 3^{λ} instead of 2^{λ})
- Outatime supports ternary and quaternary events for RTT $\leq$ 128ms

- Some impulse events delay tolerant
  - Do not speculate
  - Instead, use time compression to account for RTT delay

Checkpoint and Rollback

- Supports page-level and object-level checkpointing
  - Depends on density of Simulation State Objects (SSOs)
- Page-level checkpointing
  - Copy page on page write
  - Invalidate mis-speculated data
  - Copy back on rollback
- Object-level checkpointing
  - Use inverse functions when rolling back

Implementation

- Manually modified Doom 3 code
- Doom 3 master with multiple speculative slave versions
  - `render`
  - `undo`
  - `commit`
  - `rendercube`
- Used hardware to improve compression and video encoding

Experiment

- 3 Experiments
  - Doom 3: 23 people
  - Doom 3: 18 gamers
  - Fable 3: 23 people
- Measured on 3 metrics:
  - Mean Opinon Score
  - Skill Impact
  - Task Completion Time

Results

- Minor decrease in quality for latencies up to 128 ms
- More noticed by gamers
  - Larger/faster movements cause greater mispredictions
  - May be more sensitive as a player to such effects
- Significant reduction in skills at higher latencies
- Task completion relatively unaffected
  - Improvement over regular cloud gaming

Results

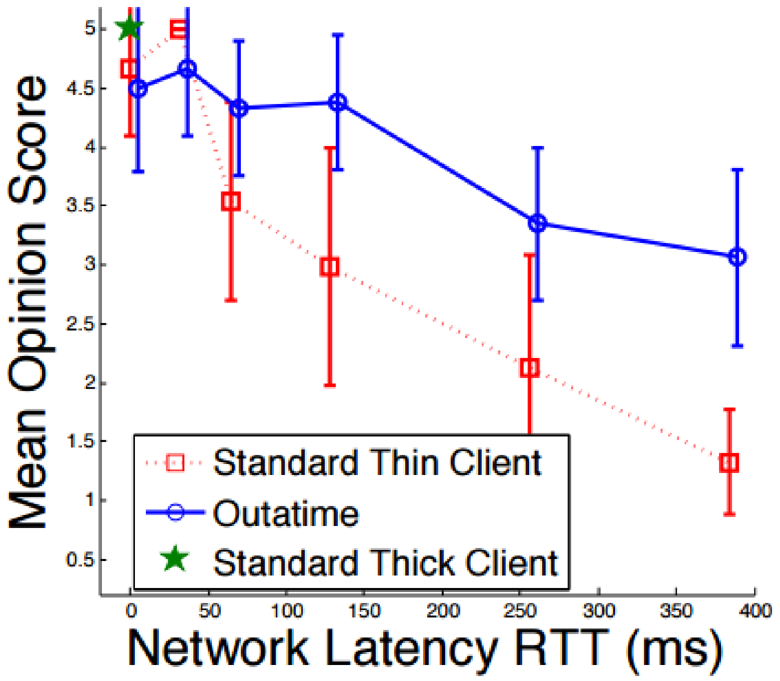


Figure 11: Impact of Latency on User Experience

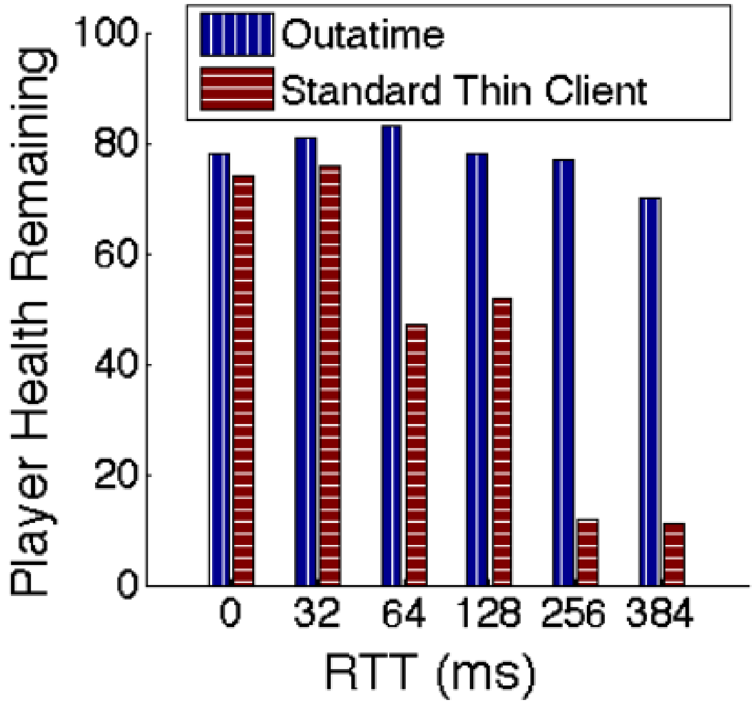


Figure 12: Remaining Health

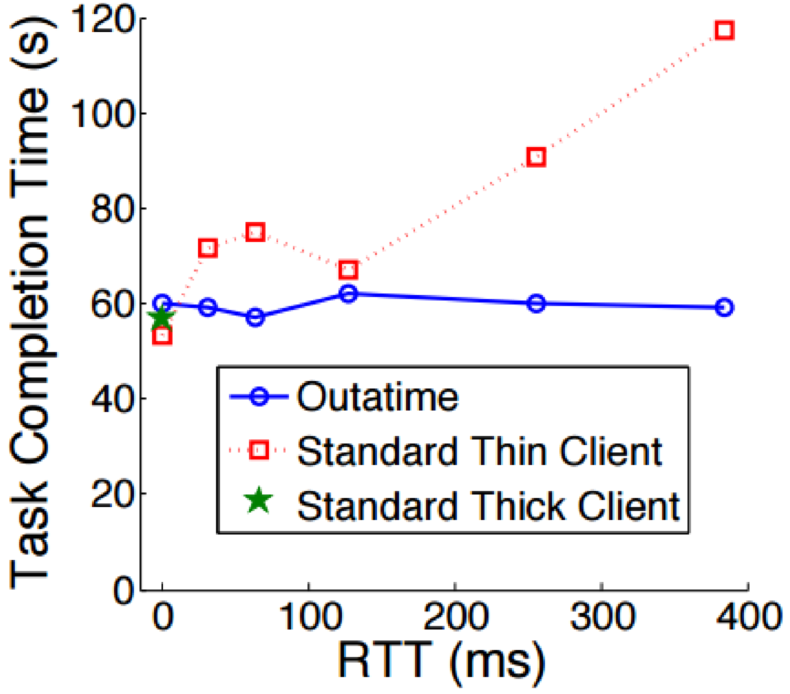


Figure 13: Task Completion Time

Performance

- Bandwidth 1.97x higher than standard cloud gaming
  - 1.04 Mbps at RTT = 128ms
- Framerate = 52fps at 95th percentile

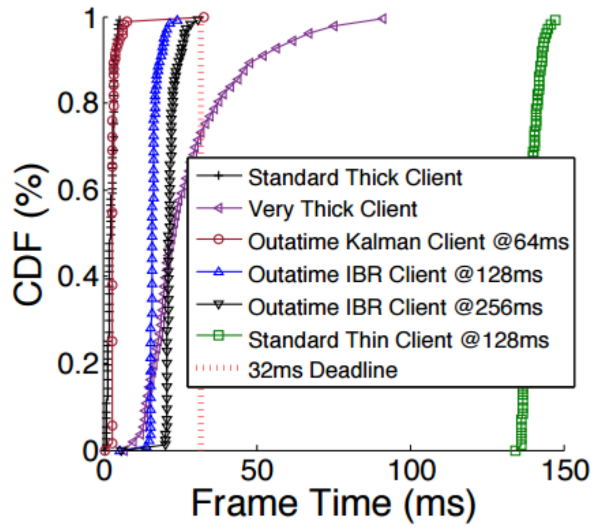


Figure 15: Client Frame Time

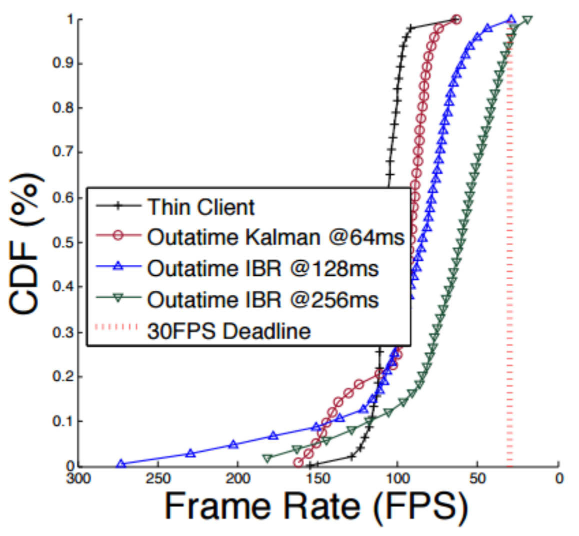


Figure 16: Frame Throughput Measured at Server

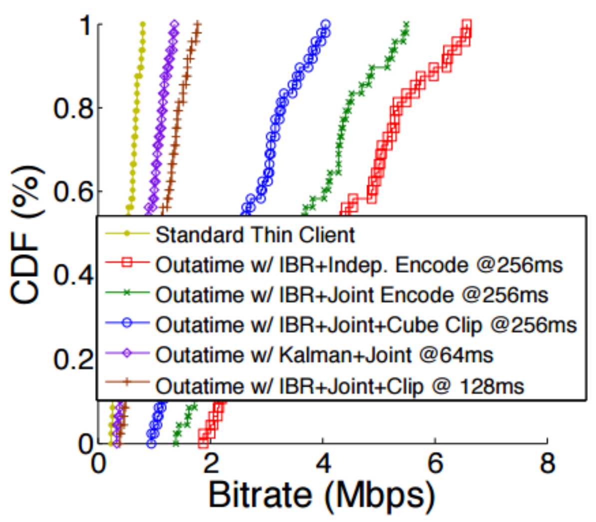


Figure 17: Bandwidth Overhead

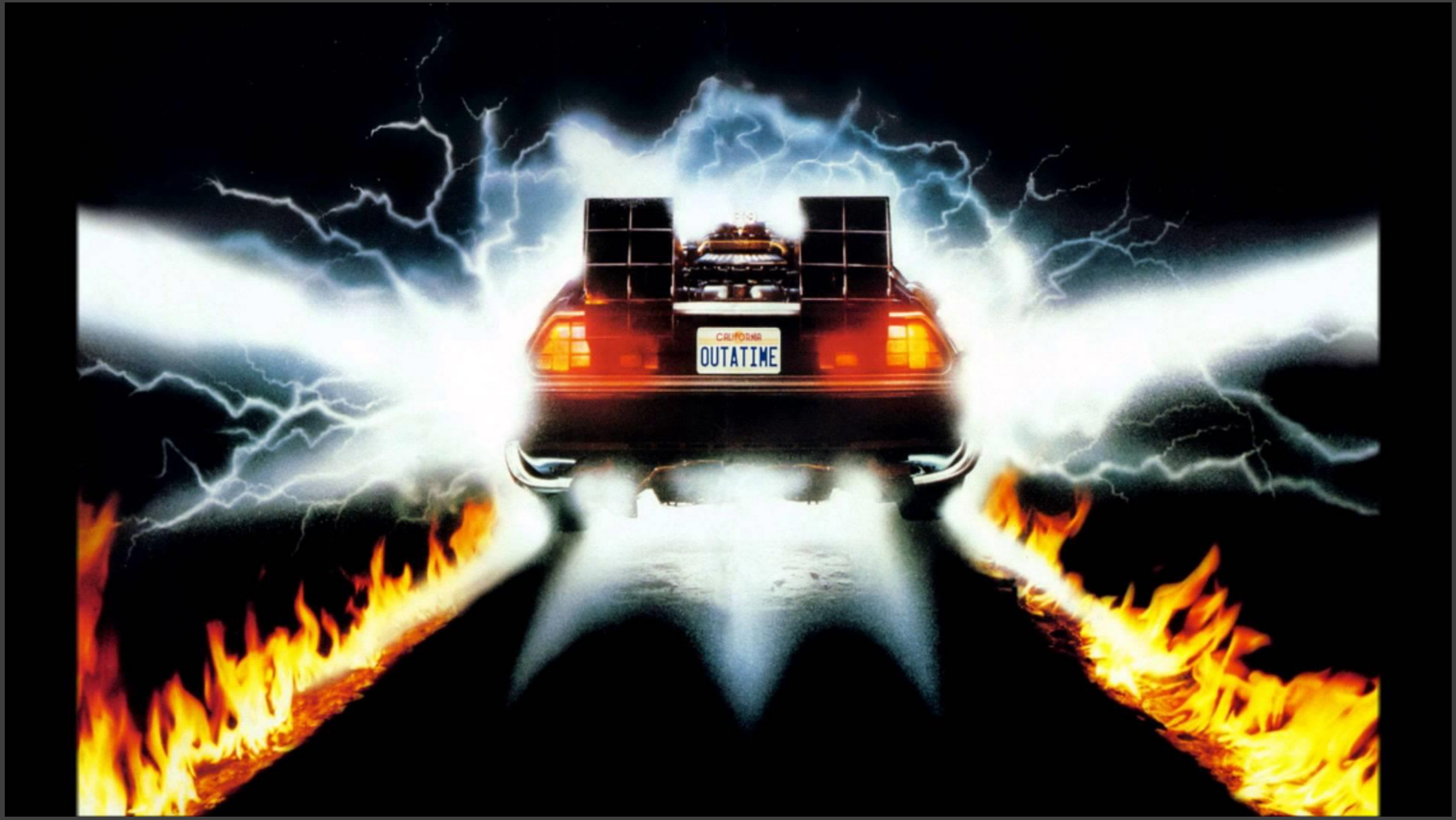
Strengths and Weaknesses

- Strengths
  - Many useful and practical tactics to minimize bandwidth
  - Effective and varied predictive measures are taken for different classifications of inputs
  - Provides foundation to make cloud gaming practical with relatively low latency
- Weaknesses
  - Does not seem scalable to games with many inputs or fast inputs (eg. RTS)
  - Requires significant code restructuring
    - Harder to use on existing games
  - Does not consider faster framerates
    - Modern games are frequently 60Hz

Reference

[1] Lee, Kyungmin, et al. Outatime: Using speculation to enable low-latency continuous interaction for mobile cloud gaming. *Proc. of MobiSys*. 2015.

Questions?



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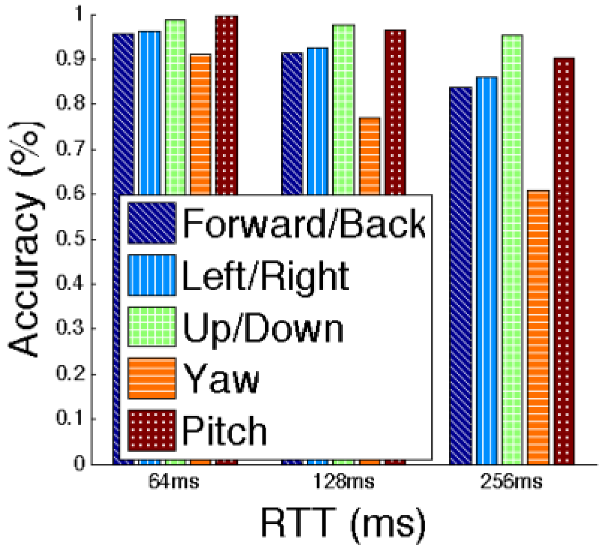
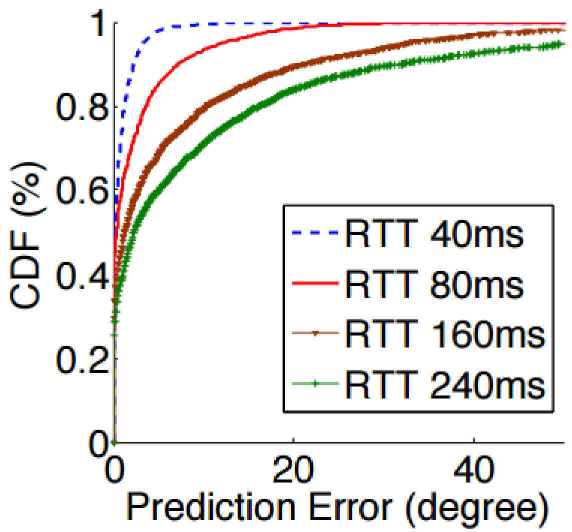
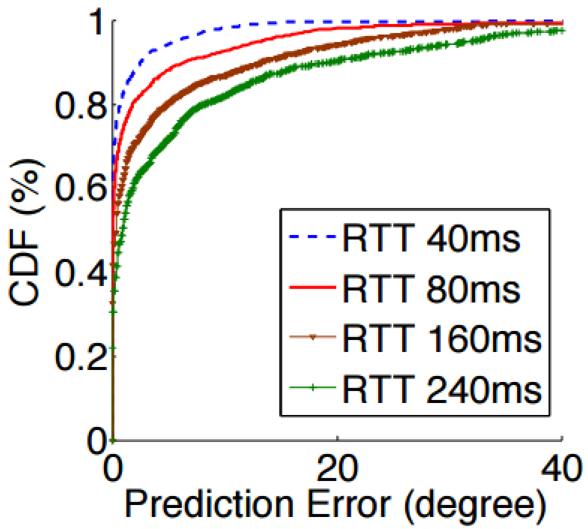


Figure 3: Doom 3 Navigation Prediction Summary. Roll (θ_z) is not an input in Doom 3 and need not be predicted.



(a) Doom 3



(b) Fable 3

Figure 4: Prediction for Yaw (θ_x), the navigation component with the highest variance. Error under 4° is imperceptible.

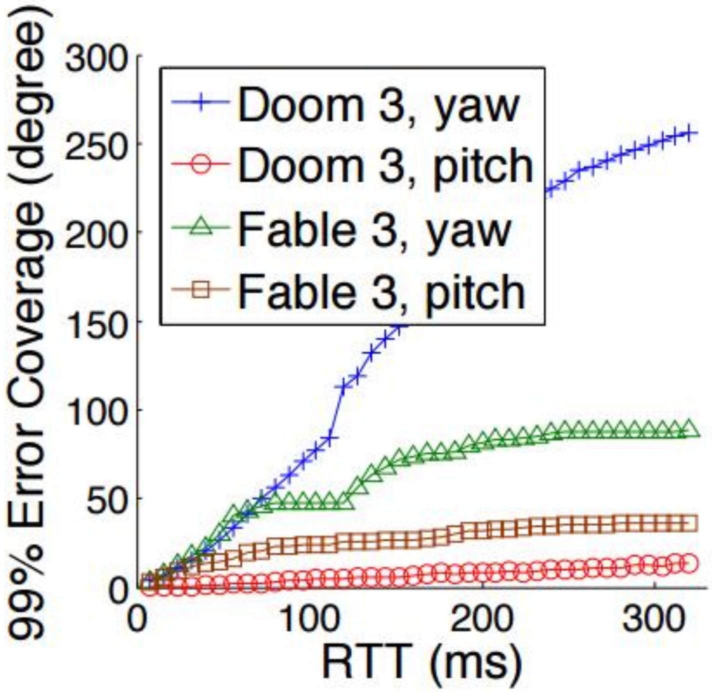


Figure 8: Angular coverage of 99% of prediction errors is much less than 360° even for high RTT.

(a) Visible Smears

(b) Patched Smears

Figure 9: Misprediction's visual artifacts appear as smears which we mitigate.