# ILLIXR: Illinois Extended Reality Testbed

**IMMERSE** — Center for Immersive Computing

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## XR: The Next Computing Interface

**Seamless integration of the virtual with the physical**

Comfortable, mobile, all day, rich immersive experiences

Virtual, augmented, mixed reality (VR, AR, MR)

Extended reality (XR)

Metaverse, digital twins, spatial computing, …

https://www.microsoft.com/en-us/research/project/holoportation-3/

Will transform most industries and human activities

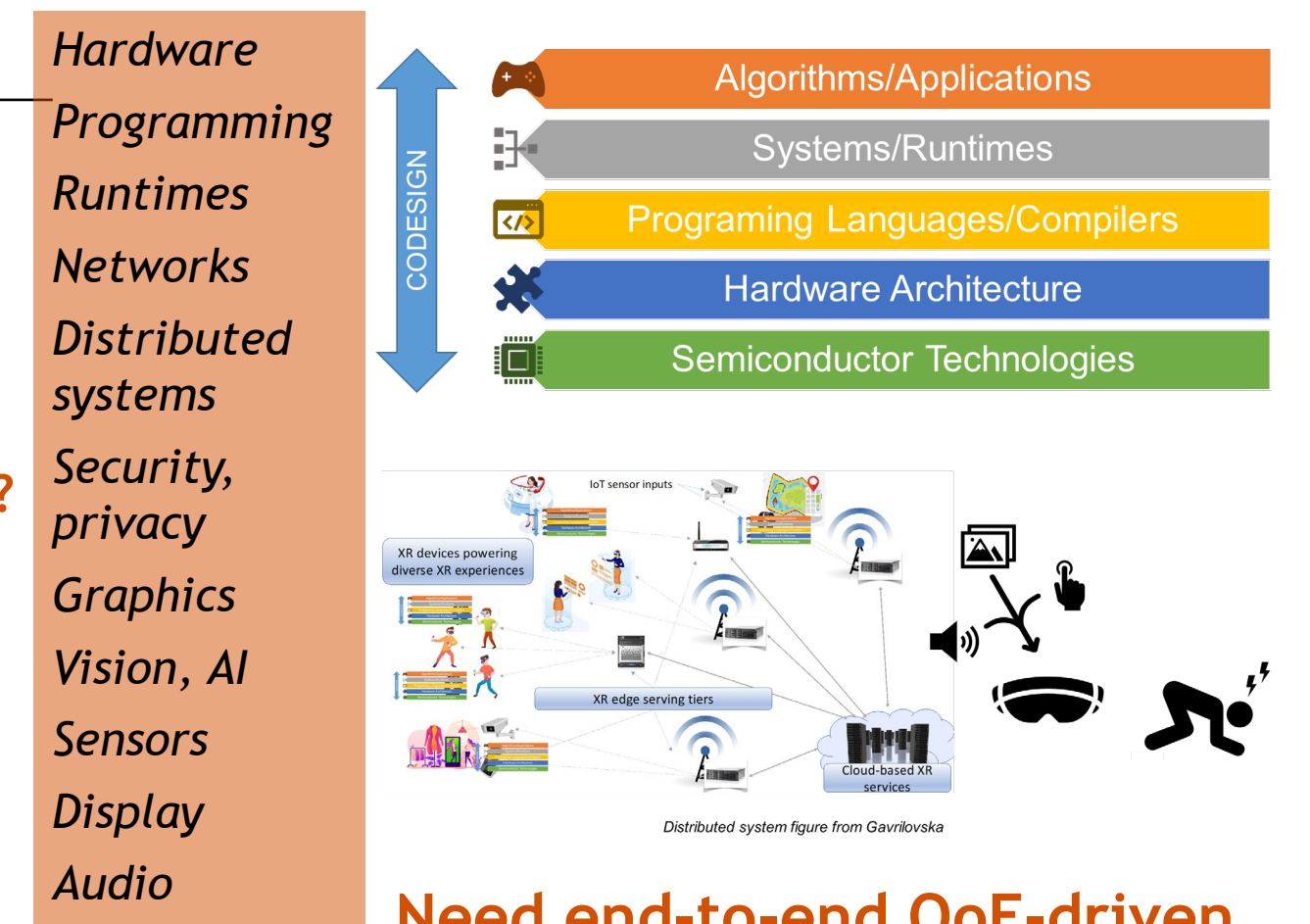Healthcare, education, science, industrial design, manufacturing, maintenance, retail, entertainment, …

## Challenges and Opportunities
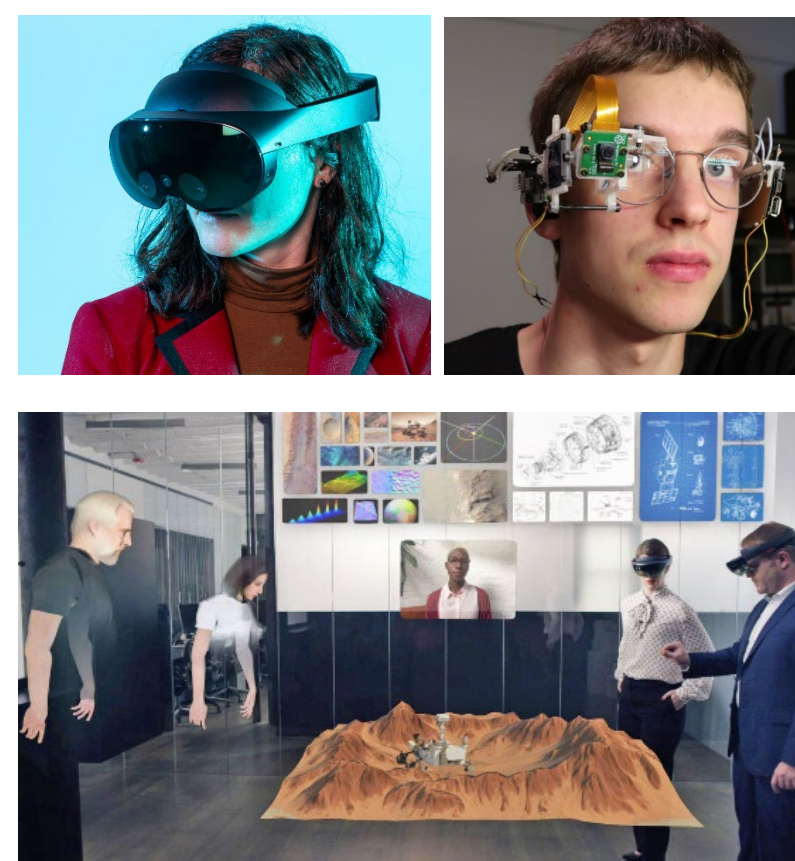
|  | Now | Desired |
|---|---|---|
| Weight (g) | 500 | 10s |
| Power (W) | 7 | 0.1 |
| Resolution (Mpixels) | 7 | 200 |
| Bandwidth (Mbps) | 100s | 1000s |
| Collaborative users | Few | 100s - ??? |

Hardware
Programming
Runtimes
Networks
Distributed systems
Security, privacy
Graphics
Vision, AI
Sensors
Display
Audio

CODESIGN:
- Algorithms/Applications
- Systems/Runtimes
- Programing Languages/Compilers
- Hardware Architecture
- Semiconductor Technologies

**Head motion to display latency**
**20ms for VR, 5ms for AR**
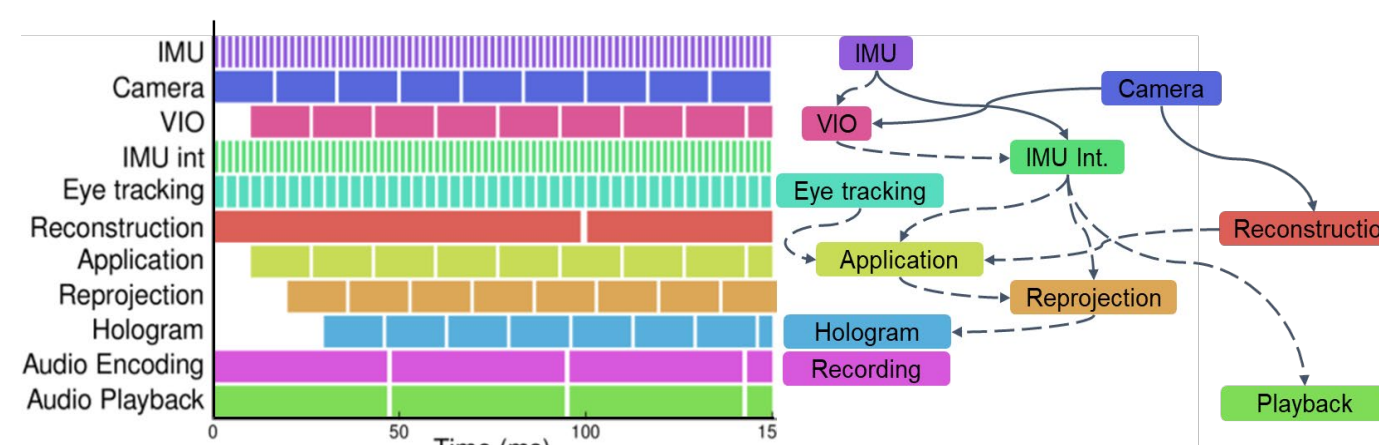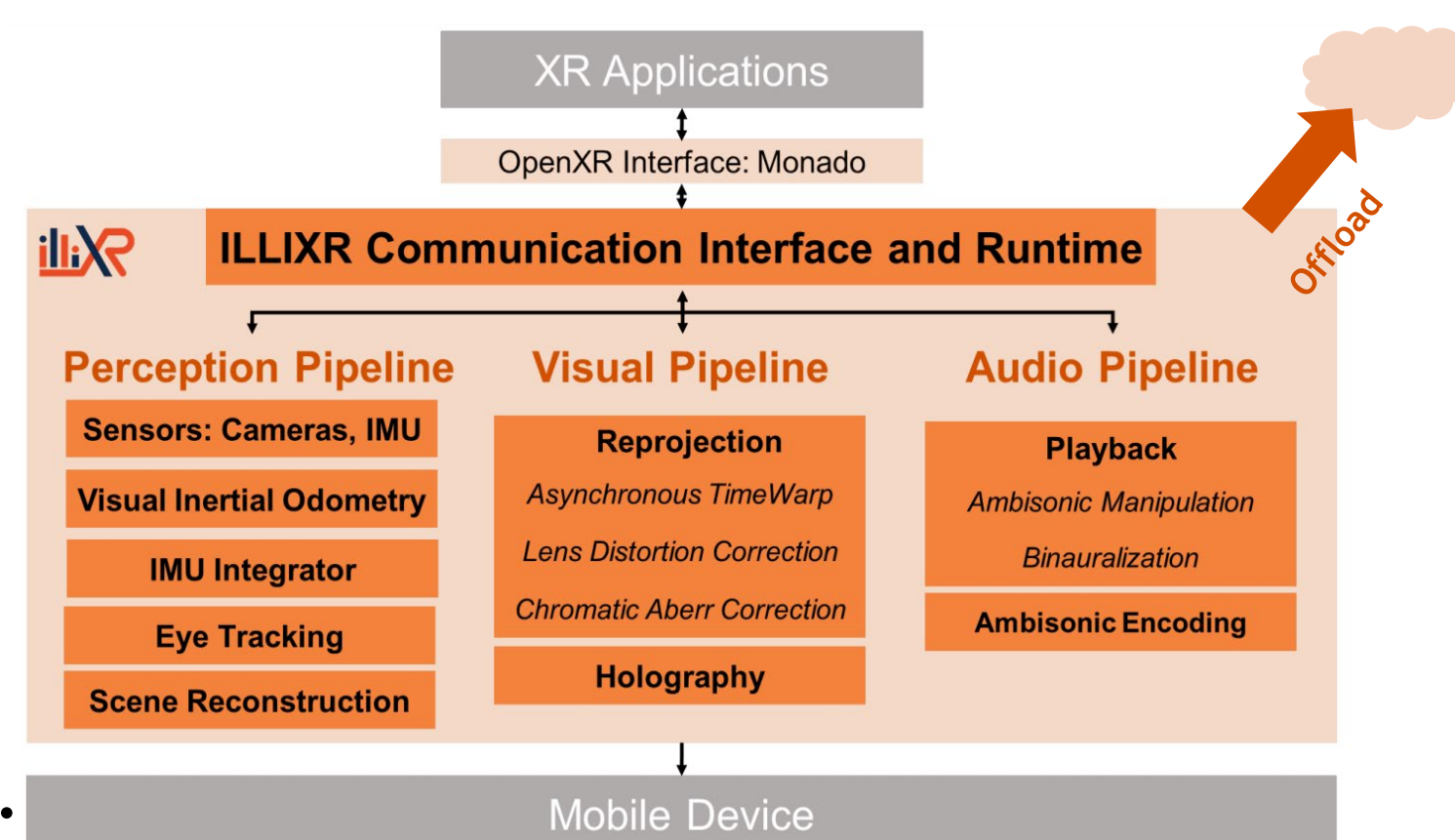
**Many more challenges**

**Need end-to-end QoE-driven, full system codesign**

*But no open reference systems or benchmarks*
*Large barrier to entry for open R&D*

## ILLIXR: Illinois Extended Reality System and Research Testbed

- ILLIXR: First open source full system XR testbed
- State-of-the-art XR components w/ modular runtime
- OpenXR compatible (using Monado)
- Extensive characterization and use for research
- ILLIXR community consortium illixr.org
- Arm, Meta, Micron, North Star, NVIDIA, academics, …
- Community meetings, active discord channels

XR Applications
OpenXR Interface: Monado
ILLIXR Communication Interface and Runtime

Offload

**Perception Pipeline**
- Sensors: Cameras, IMU
- Visual Inertial Odometry
- IMU Integrator
- Eye Tracking
- Scene Reconstruction

**Visual Pipeline**
- Reprojection
- Asynchronous TimeWarp
- Lens Distortion Correction
- Chromatic Aberr Correction
- Holography

**Audio Pipeline**
- Playback
- Ambisonic Manipulation
- Binauralization
- Ambisonic Encoding

Mobile Device

**Modular, flexible, efficient architecture**
Components are plugins
Separately compiled, dynamically loaded
Easily swap/add new components
Communication w/ event streams, shared memory

ZED Mini
Backpack PC
North Star

### Platforms tested
- Linux, Android
- PCs, NVIDIA Jetson, Samsung phone
- Various cameras, IMUs; e.g., Zed Mini
- Headset used only as display; e.g., Valve Index
- Cloud offload: AWS

### Build and install systems
- ILLIXR 3.2: cmake based, easy build, dependency & plugin management
- ILLIXR 3.0: docker and CI

### Applications, Game Engines, Graphics
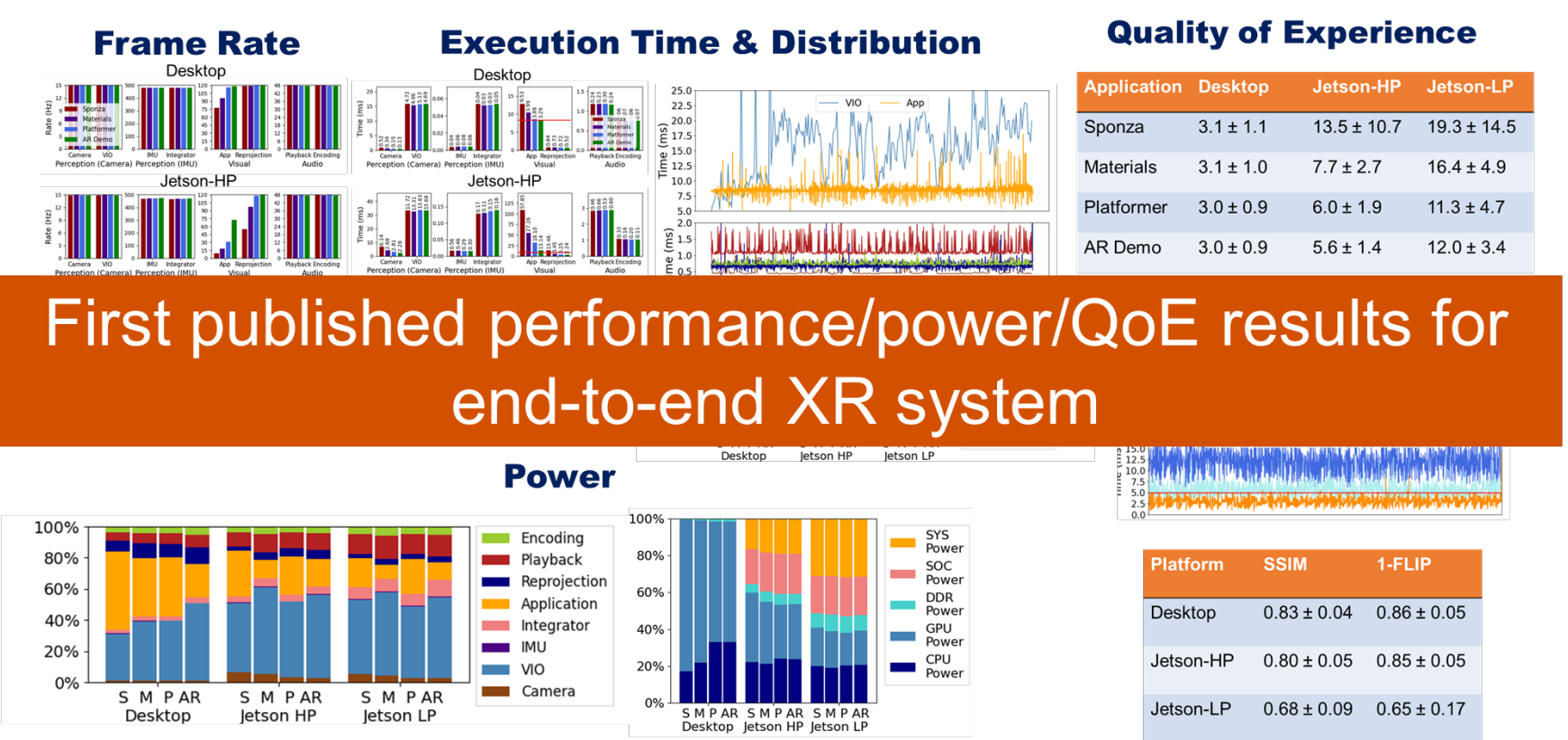- OpenXR, Unreal, Godot, Vulkan, OpenGL

### Metrics
- Motion-to-photon latency
- Image quality: SSIM, FLIP, FovVideoVDP
- Others: Frame rate, missed frames, power, …
- Extensive logging, timing infrastructure

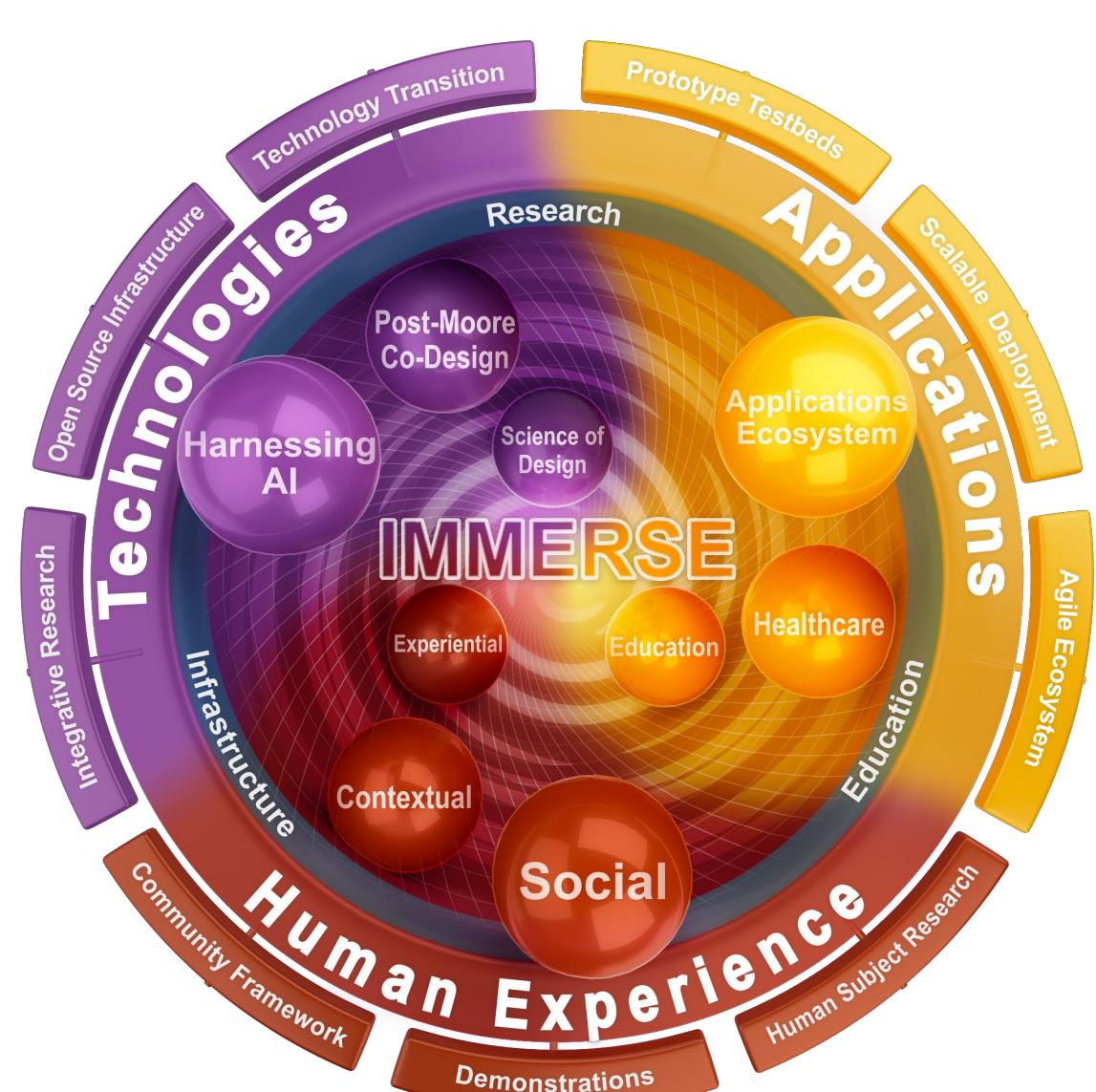## ILLIXR = Rich Playground for Systems and Applications Research

- 3D integrated sensors/compute/memory
- Represent heterogenous parallelism in SW
- Energy-efficient scene reconstruction
- Eye tracked foveated rendering
- QoE-driven scheduling
- Automated selection of accel HW/SW
- Accelerator communication interfaces

- Automated approximation
- Computation offload
- 360 video streaming
- Multiuser distributed XR
- QoE metrics
- XR algorithms
- Security and privacy

*Arm*
*Cisco*
*CMU*
*Georgia Tech*
*Harvard*
*IBM*
*Illinois*
*Intel*

*Meta*
*Michigan*
*NCSU*
*Nvidia*
*Oulu*
*Penn State*
*Purdue*
*…*

Frame Rate | Execution Time & Distribution | Quality of Experience

**First published performance/power/QoE results for end-to-end XR system**

Power

## Ongoing Work

### IMMERSE Center for Immersive Computing

- IMMERSE brings together immersive technologies, applications and human experience
- Integrating ILLIXR with application driven XR testbeds for healthcare, education, and others
- Understanding user experience in application context

### Ongoing ILLIXR Development and Use

- Multi-user XR: ILLIXR – ARENA integration
- User studies infrastructure
- XR datasets
- Offloading rendering and scene reconstruction
- Foundation models: speech to rendered volumetric scenes, editing
- Privacy-aware offloading
- Portable support for accelerators
- Broader hardware and software support
- Integrating emulated/simulated hardware in the loop
- Integration with IMMERSE healthcare, applications testbeds