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Wireless Communication Challenges for Extended (Augmented and Virtual) Reality (XR)

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- I.F. Akyildiz and H. Guo, "Wireless Communication Challenges for Extended Reality (XR)", ITU Journal FET (Future and Evolving Technologies), 2022.

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REALITY & VIRTUAL REALITY

Reality:

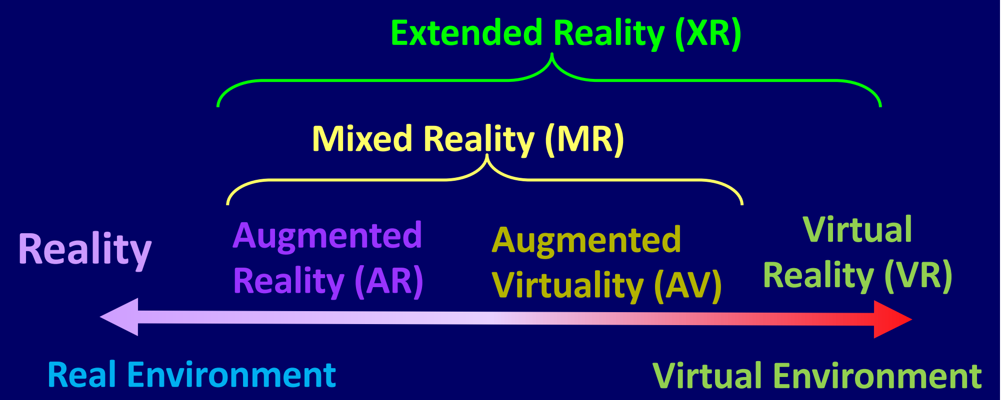
- Human perception of real objects is based on five basic senses: *Sight, Hearing, Touch, Smell, and Taste*

Virtual Reality (VR):

- Creating digital virtual objects to represent the same real senses and environments

XR, AR, MR and VR

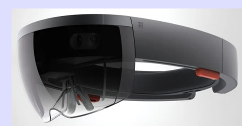
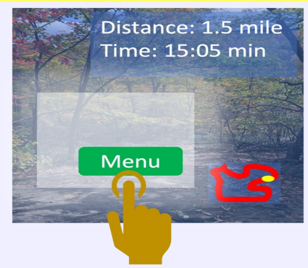
- XR (eXtended Reality) is an umbrella term for
  - Augmented Reality (AR)
    - Real environment is augmented with virtual objects and information
  - Virtual Reality (VR)
    - Fully virtual environment → not related to user's surrounding real environments
  - Mixed Reality (MR)
    - A mixture of real and virtual environments
    - Low percentage of virtual contents → AR
    - High percentage of virtual contents → AV



Reality-Virtuality Continuum

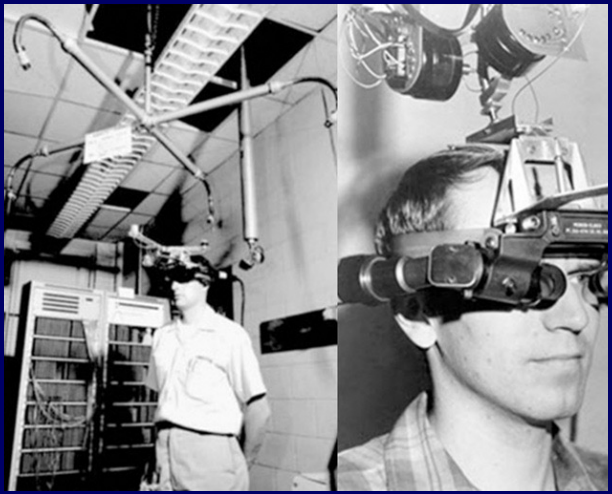
P. Milgram and F. Kishino,
"A Taxonomy of Mixed Reality Visual Displays"
IEICE TRANSACTIONS on Information and Systems, 1994.

DEVICES & USE CASES

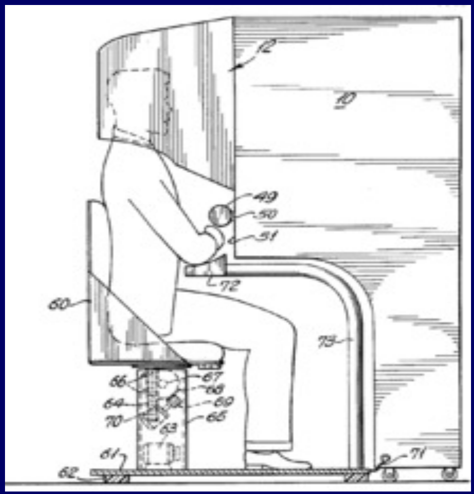
		Extended Reality (XR)		
	Reality	Augmented Reality (AR)	Mixed Reality (MR)	Virtual Reality (VR)
Display	Naked Eye/Optical Glasses	Translucent Display	Translucent Display	Occlusion Display
Display Example				
Example	 Real View of a Trail	 Augmented Virtual Map and Direction	 Interactive Virtual Contents	 Virtual Gaming

Beginning History

- Sword of Damocles Augmented Reality (AR) machine in 1968
- Sensorama Virtual Reality (VR) Machine in 1962



Sword of Damocles



Sensorama

TODAY'S XR Devices

- Tethered by Cables

- Wireless Solutions for XR ?

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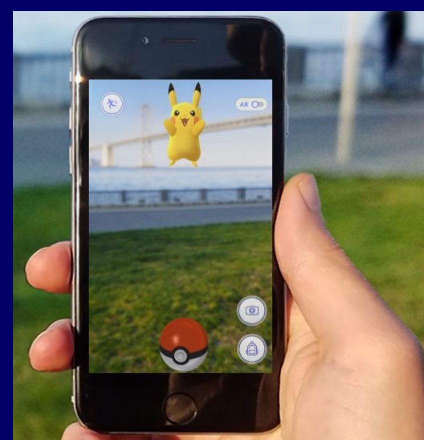
AUGMENTED REALITY (AR)

- **Contents**
  - Virtual Objects: Pokemon GO
  - Virtual Information: Assistance
- **Devices**
  - Non-immersive AR: Smart devices, e.g., cell phones, ipads, computers
  - Immersive AR: Optical Head Mounted Displays



Source: vg247.com

Source: assemblymag.com

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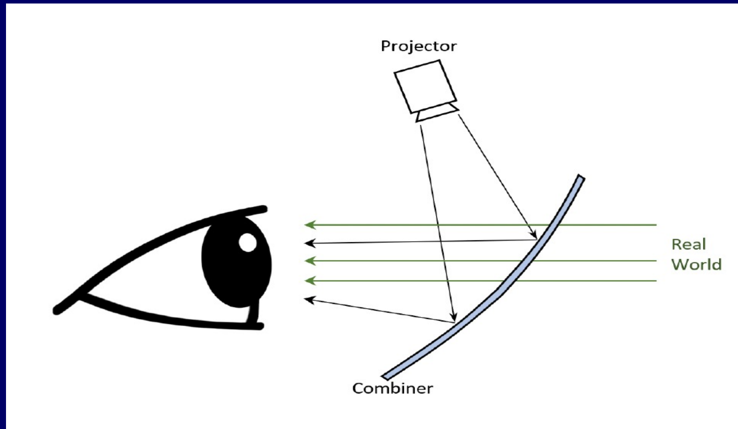
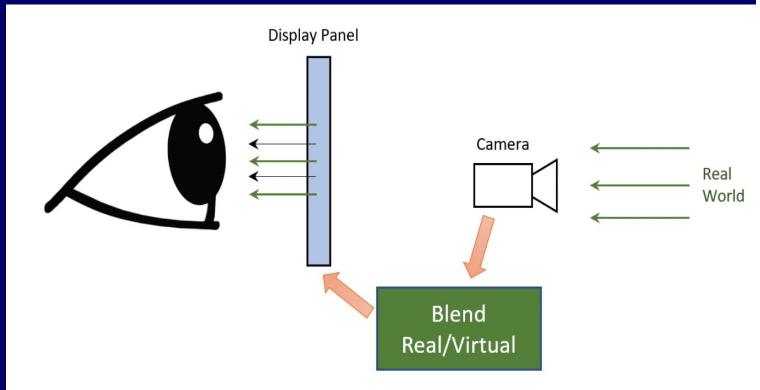
IMMERSIVE VS NONIMMERSIVE

- **Optical see-through (immersive)**
  - Majority of the high-end AR devices use this technology
  - Users can observe the real environment



- **Video see-through (immersive & nonimmersive)**
  - e.g., smart devices with cameras
  - Virtual contents are augmented to videos
  - Users observe the real environment through the camera



D. Wagner, L. Noui, A. Stannard, "Why is making good AR displays so hard?", 2019

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MIXED REALITY (MR)

- **Contents**
  - Active virtual contents
  - Users can interact with the virtual contents

- **Devices**
  - Optical Head Mounted Displays
  - Example: Microsoft HoloLens uses 802.11ac 2x2 Wi-Fi radio (Wireless)

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VIRTUAL REALITY

- **Contents**
  - Virtual or digital objects, information, videos, etc.
- **Devices**
  - Low-cost: Google Cardboard → provide VR experiences
  - Head Mounted Displays

Source: computingnews.com

Source: archdaily.com

HTC vive

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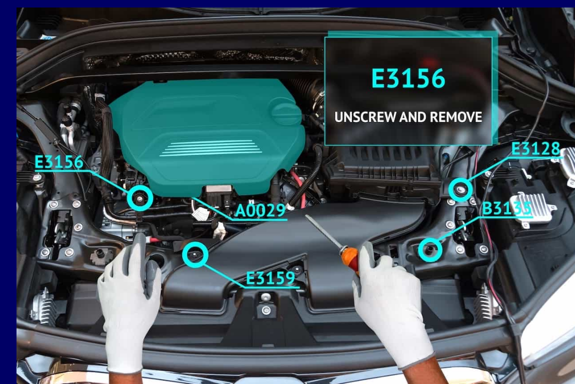
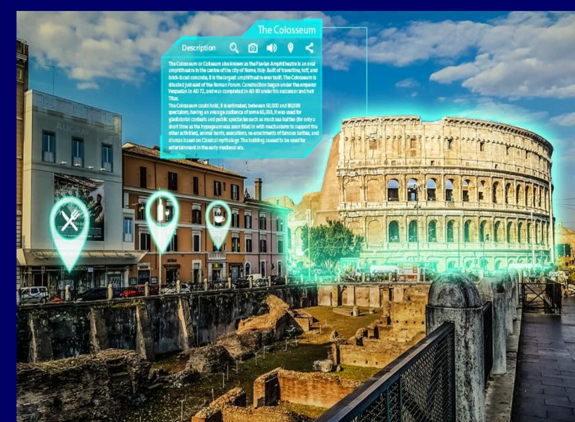
USE CASES: AR

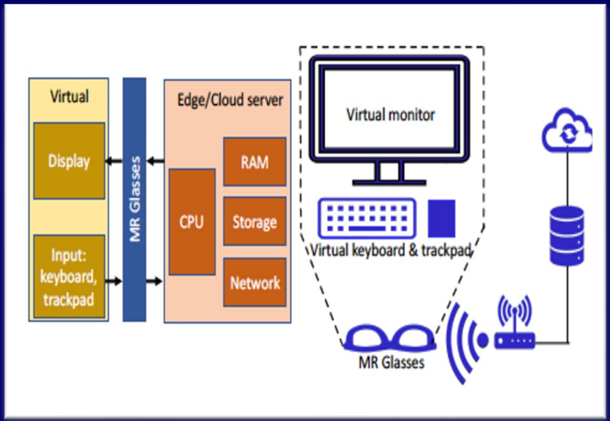
- Sports
- Automotive
- Real Estate
- Tourism

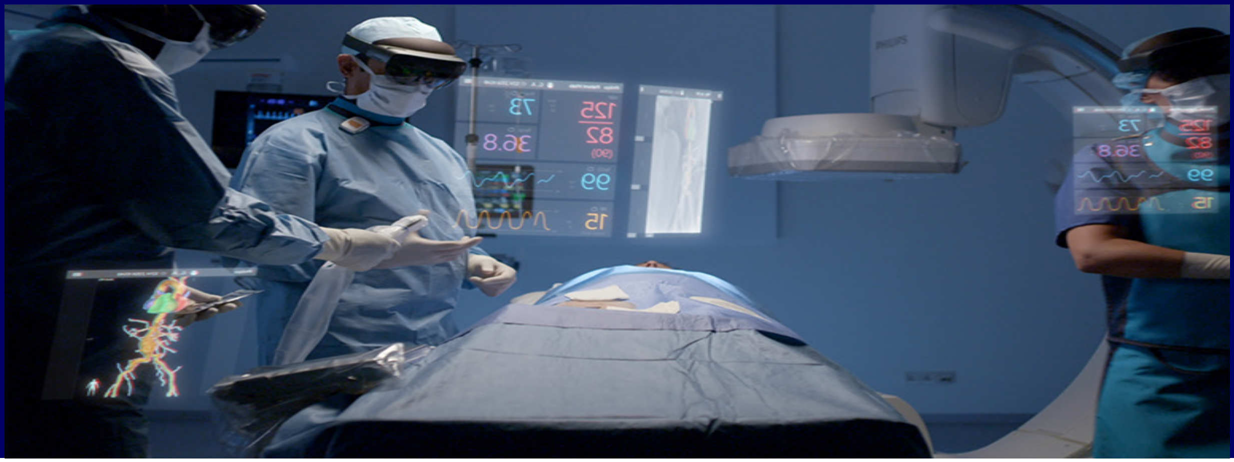




USE CASES: MR

- Virtual Computing Environment
  - Virtual computer
  - 3D Design
  - Healthcare





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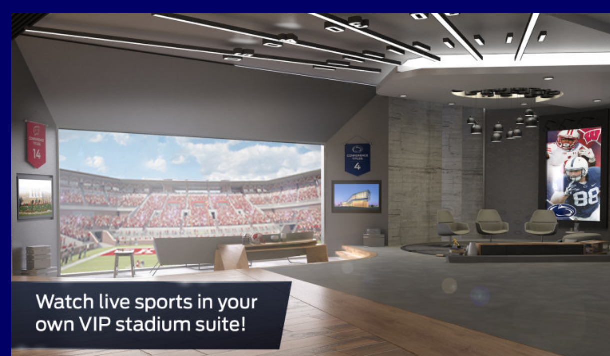
USE CASES: VR

- Personal Movie Theater
- Sports
- Gaming



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EXISTING DEVICES

	Vendor	Model	Weight (g)	Display (per eye)	Refresh rate (Hz)	Human understanding	Storage (GB)	Memory (GB)	Connectivity	Power (Hour)
AR	Epson	Moverio BT300	69	1280×720	30	controller	16	2	Wi-Fi, Bluetooth, cable	~6
	VUZIX	M4000	~246	854×480	–	touchpad, voice,buttons	64	6	Wi-Fi, Bluetooth, cable	2 to 12
MR	Microsoft	HoloLens2	566	2K	120	head/eye/hand tracking	64	4	Wi-Fi , Bluetooth	2 to 3
VR	Oculus	Quest 2	503	1832×1920	72	controller	256	6	Air Link (wireless)	2 to 3
	HTC	Vive Cosmos Elite	–	1440×1700	90	controller	–	–	cable, wireless adapter (60GHz)	2.5 (wire-less)
	Huawei	VR Glass	166	1600×1600	90	controller	–	–	cable	–
	HP	Reverb G2	550	2160×2160	90	controller	–	–	Bluetooth, cable	–

oculus

Microsoft

EPSON EXCEED YOUR VISION

HUAWEI

htc







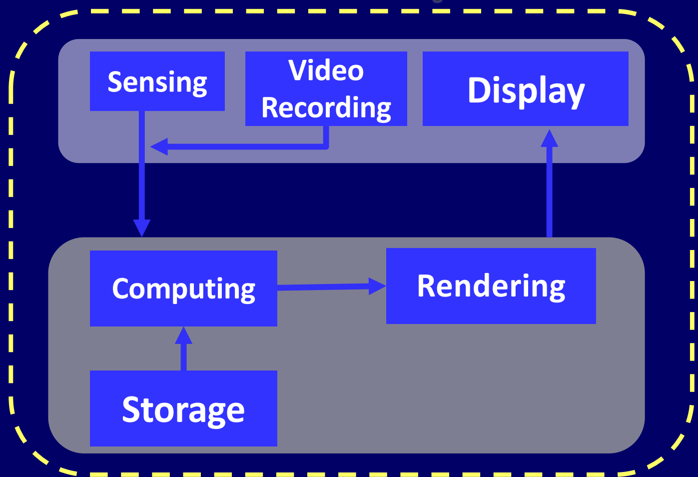
CONSTRAINTS OF EXISTING DEVICES

- Currently, XR content rendering mainly relies on wired connections
  - Not flexible & limited mobility
- Wi-Fi and Bluetooth can be used, however,
  - Mainly for low-data-rate applications, e.g., system updates, software download, message, weather, email, location, etc.
  - Intel WiGig using 60 GHz mmWave has been adopted: 3 players within 7 m → limited number of users & also short ranges
- High power consumption → limited operation time & heat
- Heavy weight problem → not practical and not wearable

ALL-IN-ONE SYSTEM ARCHITECTURE

- Applications are pre-installed in XR headsets/glasses using wireless/wired communications
- Otherwise self-sustained
- Pros: low latency, not tethered
- Cons: very limited functionalities due to limited storage, energy, and computing resources

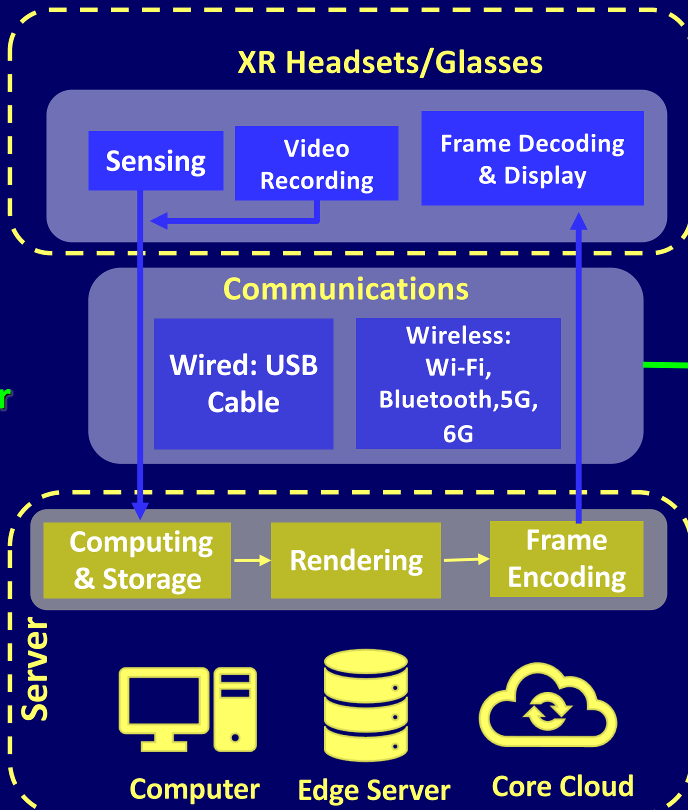
XR Headsets/Glasses

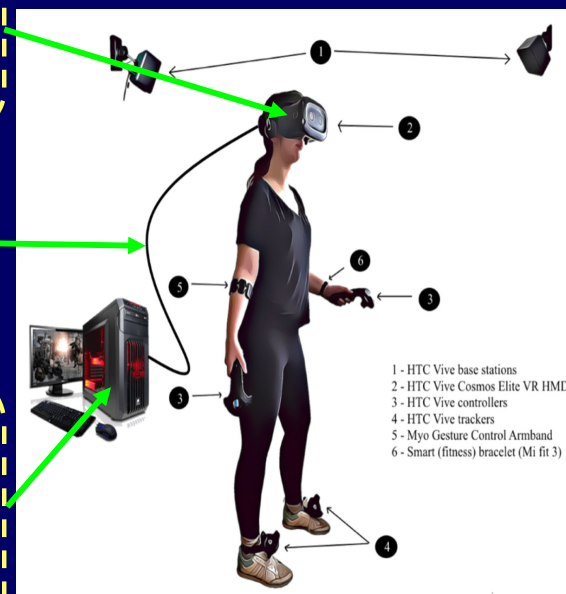


Not the focus of this talk!

SERVER-SUPPORTED ARCHITECTURE

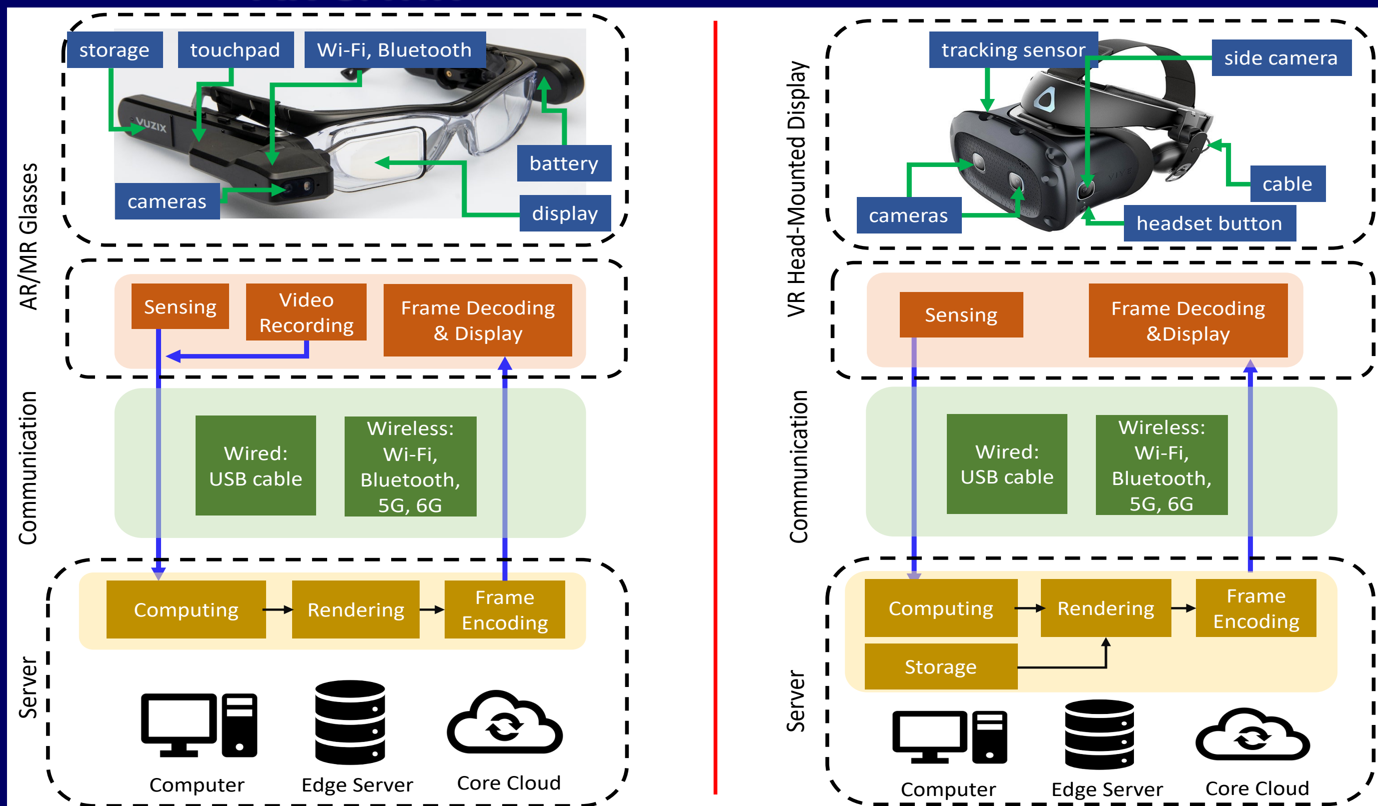
- Computing and storage are offloaded to servers,
  e.g., computers, edge and cloud servers
- Pros:
  i) reduce size, weight, and power consumption of headsets
  ii) support complex applications
- Cons:
  require wired/wireless communications





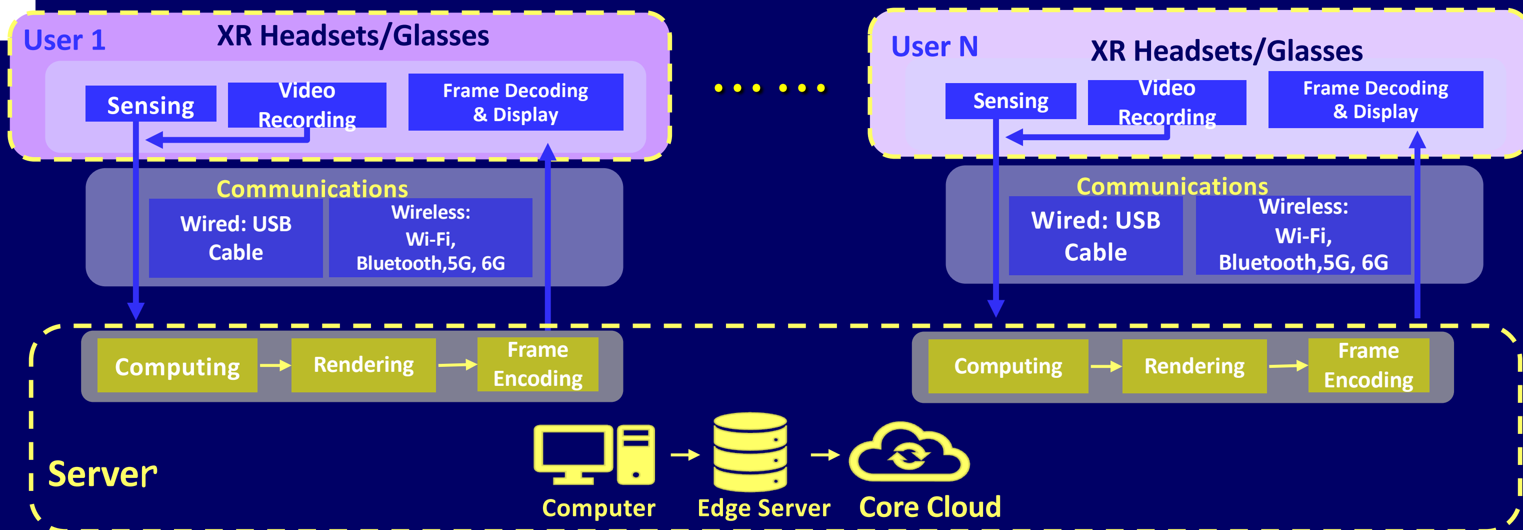
SUMMARY: AR, MR & VR SYSTEM ARCHITECTURE

AR & MR | VR



AR Glasses is VUZIX M4000 and VR HMD is HTC Vive Cosmos Elite

MULTI-USER SYSTEM ARCHITECTURE



1. Multiple users connected to the same computer using cables (Wired mainly)
2. Multiple users connected to the same local area network (Centralized Architecture)
3. Multiple users can be in different networks and served by different servers (Distributed Architecture)

SUMMARY OF DIFFERENCES

	AR	MR	VR
Display	Translucent	Translucent	Occlusion
Human Understanding	Integrated with OHMD & Artificial Intelligence	Integrated with OHMD & Artificial Intelligence	External Controllers & Artificial Intelligence
Environment Understanding	Artificial Intelligence	Artificial Intelligence	Not Required
Uplink	Broadband	Broadband	Limited Data Rates
Downlink	Broadband	Broadband	Broadband
Latency Requirement	High	High	Weak Interactive: Low Strong Interactive: High

From users' headsets to the server

From the server to users' headsets

Free users' hands to improve work efficiency

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TECHNICAL REQUIREMENTS

C. Flavián, S. Ibáñez-Sánchez, and C. Orús.
The influence of scent on virtual reality experiences: The role of aroma-content congruence
Journal of Business Research123 (2021): 289-301.

	Sight	Hearing	Touch	Smell	Taste
XR	✓	✓	✓	✗	✗
Video	✓	✓	✗	✗	✗
Document	✓	✗	✗	✗	✗

- **Human perception relies on 5 senses**
  - Sight, hearing, touch, smell, and taste
- **XR mainly uses sight, hearing, and touch**
  - Some smell add-ons are available, but not widely used
- **Current Grand Challenges of Wireless XR :**
  - High-Quality Video Transmission (Uplink and Downlink)
  - Future Hapic (Touch) communication (under development), e.g., remote surgery: a surgeon's actions are transmitted to and replicated by a robot in a remote emergency room
- **Audio and Touch may not be a problem because**
  - Audio (hearing) files are relatively small

COMPUTATION OF DATA RATE AND LATENCY

- **Data Rate =** Resolution × Refresh Rate × Bits of color (8 or 12) × 3 (RGB) × 2 (two eyes)
- **End-to-End Latency =** (Sensing + Video Recording) + UL Delay + Server Delay + DL Delay + (Decoding + Display)
- **Resolution:**

  Measurement of a video frame's width and height in pixels
  - Resolution = Vertical Degree (from FoV) × PPD × Horizontal Degree (from FoV) × PPD
- **Field-of-View (FoV):**

  Angle of the maximum area that we can observe (≈130° per eye and ≈180° for two eyes)
- **Pixels-Per-Degree (PPD):**

  Number of pixels that are in the view for each degree
- **Refresh Rate:**

  Number of video frames that can be displayed in one second, e.g., 90 Hz

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EXAMPLES OF XR PARAMETERS

	Screen	Environment	Uplink	Downlink	Latency	Refresh Rate	Pixels per Degree	Field of View
AR	Translucent	Passive Virtual + Real	0.02 – 1.0 Gbps	0.02 – 1.0 Gbps	15 ms	90 Hz	30 - 60	20° - 50°
MR	Translucent	Passive/Active Virtual + Real	0.02 – 1.0 Gbps	0.02 – 1.0 Gbps	10 ms	90 Hz	30 - 60	20° - 50°
VR	Occlusion	Virtual	150 kbps	0.02 – 1.0 Gbps	20 ms	90 Hz	10 - 15	100° - 150°
Ultimate MR	Translucent	Passive/Active Virtual + Real	<2.3 Tbps	2.3 Tbps	<8.3 ms	120 Hz	64	360°
Ultimate VR	Occlusion	Virtual	<2.3 Tbps	2.3 Tbps	<8.3 ms	120 Hz	64	360°

- Future advanced MR and VR with unprecedented quality-of-experience
- Ultimate AR will converge to Ultimate MR since MR is more powerful than AR
- Ultimate XR includes ultimate MR and VR

DATA RATES

- **Existing XR**
  - Resolution 1440 × 1700; refresh rate 90 Hz; bit of color 8
  - Required uncompressed data rate: 10.6 Gbps
  - Use a 300:1 compression rate: 35.3 Mbps
- **Ultimate XR**
  - Full-view 360° × 180°; PPD 65; refresh rate 120 Hz; bit of color 12
  - Required uncompressed data rate: 2.3 Tbps
  - Use a 300:1 compression rate: 7.7 Gbps
  - Required uncompressed data rate with reduced FoV (110° × 110°): 428.2 Gbps → use a 300:1 compression rate: 1.4 Gbps

LATENCY

- Applications require different latencies
  1. App1: AR, MR, and high-interactive VR (e.g., gaming)
  2. App2: Low-interactive VR (e.g., personal movie theater)

- Existing XR Requirements
  - App1: < 20 ms
  - App2: < 10 - 20 s

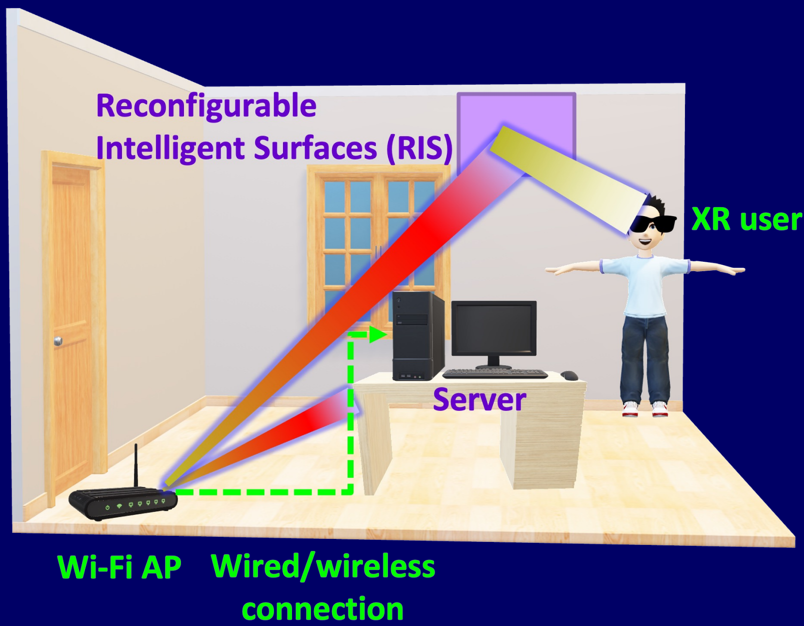
- Ultimate XR Requirements
  - End-to-End latency < 8.3 ms
  - Including encoding, communication, networking, decoding, display, etc.

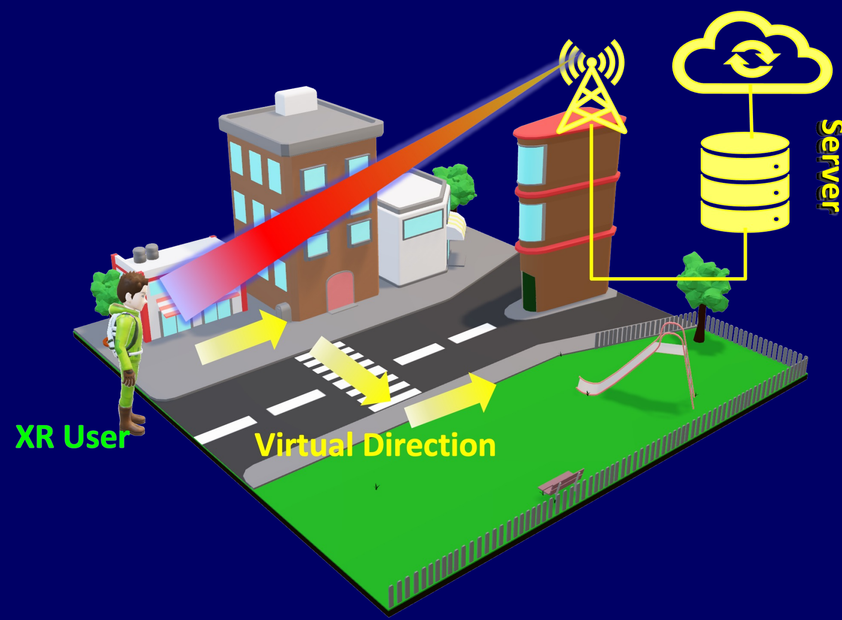
RESEARCH CHALLENGES

- Data Rates
- Latency
- Artificial Intelligence-assisted Wireless XR
- Mobility
- Power Consumption and Weight
- Collaborative XR
- Research Testbeds
- Security and Privacy
- Wireless Sensing

LAXR & WAXR

- **LAXR:** Local Area Extended Reality (VR, AR and MR) → Wi-Fi
- **WAXR:** Wide Area Extended Reality (VR, AR and MR) → 5G, 6G





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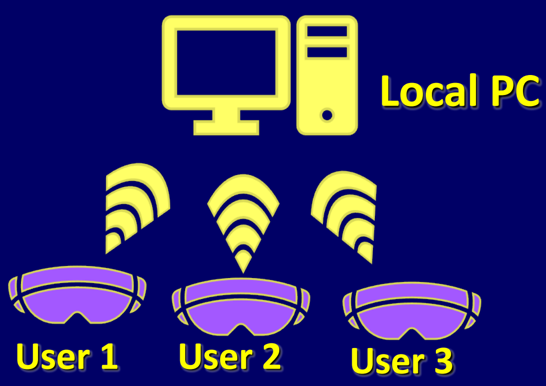
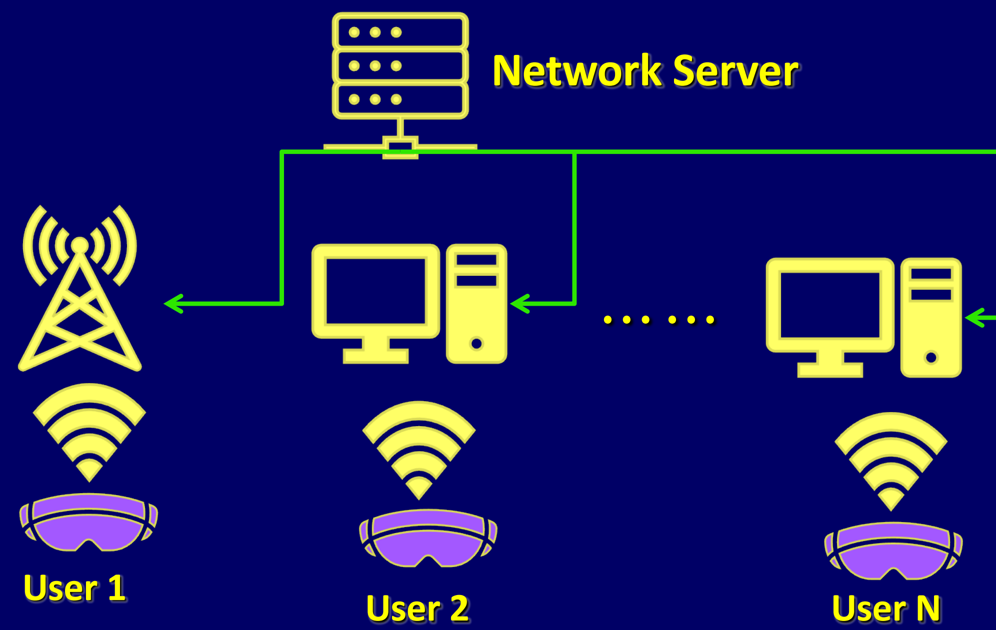
MULTI-USER LAXR & WAXR

- **LAXR**
  - Users are in the same local area network
  - Use Cases: VR gaming, MR collaborative design



- **WAXR**
  - Users are from a large geographic area with different access technologies
  - Use Cases: VR conference, VR broadcasting



MOBILE AR, MR & VR

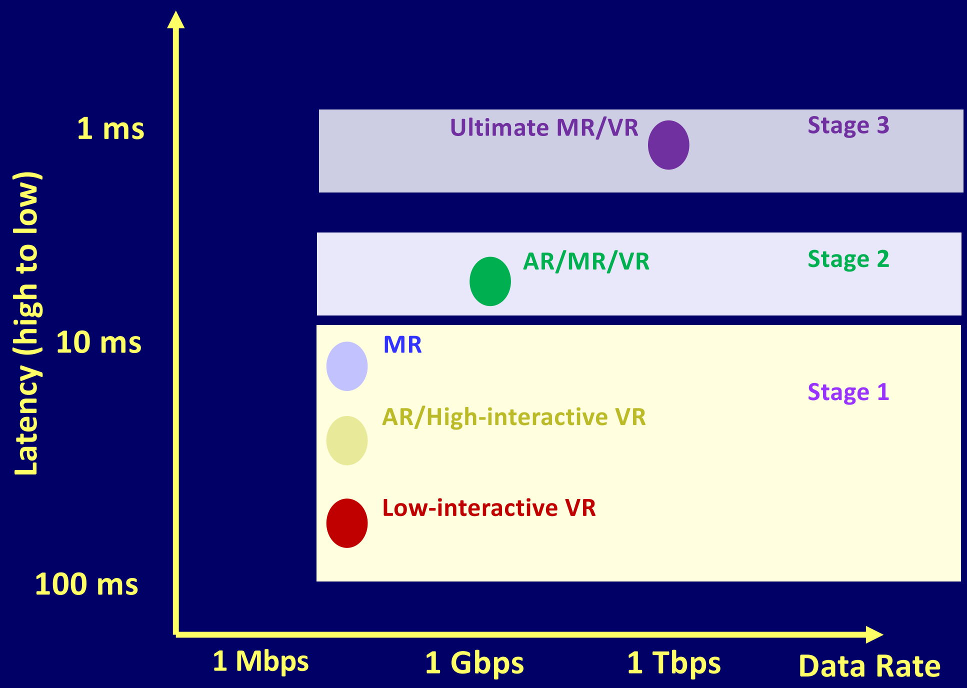
- WAXR supports mobile AR, MR & VR
  - Tourism, automobile, navigation, etc.

- Mobile VR is different from mobile AR & MR
  - VR user cannot observe the real environment
  - VR user cannot move in a wide area without external help → dangerous

- Mobile VR in a wide area
  - VR entertainment services on a train, bus, taxi, street park, etc.

ULTIMATE XR

- Ultimate XR will provide ultra-low latency (lower than 1 ms) high-quality immersive experiences, which is stage 3
- Ultimate AR will converge to Ultimate MR since MR is more powerful than AR
- Existing XR is at stage 1



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DATA RATES

- D. Xu, et al.
  "Understanding operational 5G: A first measurement study on its coverage, performance and energy consumption" ACM Sigcomm'20.
- A. Narayanan et al.
  "A first look at commercial 5G performance on smartphones." WWW'20.
- E. Khorov, I. Levitsky, and I. F. Akyildiz.
  "Current status and directions of IEEE 802.11 be, the future Wi-Fi 7." IEEE Access (2020)
- I.F. Akyildiz, A. Kak, and S. Nie.
  "6G and beyond: The future of wireless communications systems." IEEE Access (2020)

- **Limitations of 5G Wireless Systems**
  - 20 Gbps peak data rates
  - However, measurements show the achievable data rate is around 0.1 to 2.0 Gbps → Support existing XR, but NOT sufficient for ultimate XR
- **LAXR: Next Generation Wi-Fi Systems**
  - 802.11 be: around 46 Gbps
  - 802.11 ay: around 100 Gbps
- **WAXR: 5G + 6G Wireless Systems**
  - 6G peak data rate 1 Tbps and experienced data rate 1 Gbps

RESEARCH DIRECTIONS TO IMPROVE DATA RATES

- I.F. Akyildiz, A. Kak, and S. Nie.
  "6G and beyond: The future of wireless communications systems" IEEE Access (2020).
- I. F. Akyildiz, et al.
  "Terahertz band communication: An old problem revisited and research directions for the next decade"
  arXiv preprint arXiv:2112.13187 (2021)
- C. Liaskos, et al.
  "The Internet of MetaMaterial Things and their Software Enablers."
  ITU Journal FET, (2020).

- Optimal 6G and beyond wireless system design
  - mmWave, Terahertz, and Visible Light Communication (VLC)
  - Optimal resource allocation
  - Co-design of sensing, communication and intelligence
- Reconfigurable intelligent surface in unreliable/blocked environments
  - Adaptive beamforming considering user motion and wireless environment
- Multi-users
  - Medium Access Control
  - Interference

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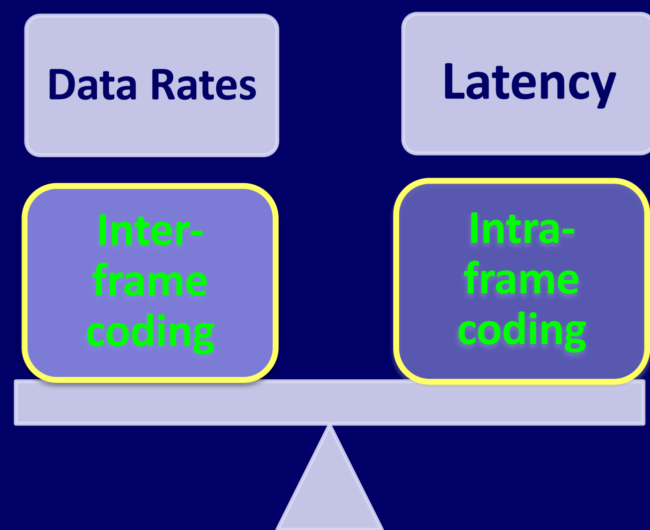
LATENCY

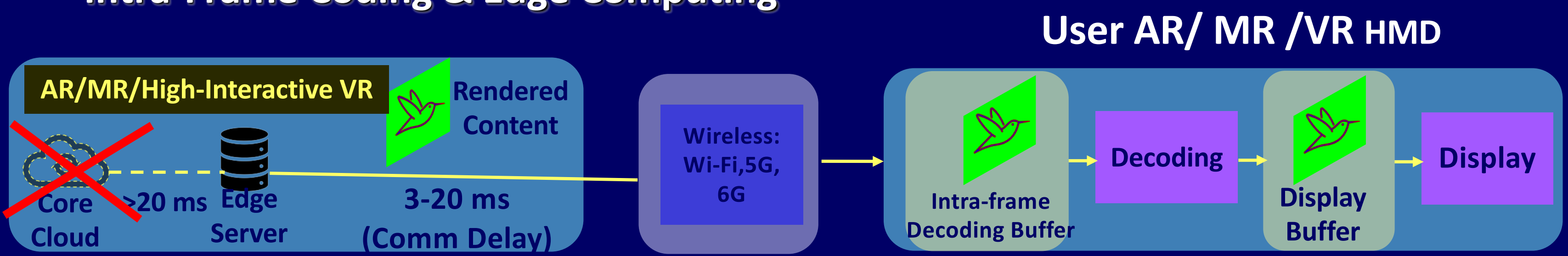
- **Intra-frame Coding**
  - Compression in a single frame
  - Low compression rate (require high data rates) → low latency

- **Inter-frame Coding**
  - Compression among multiple frames (buffer frames)
  - High compression rate (require low data rates) → long latency

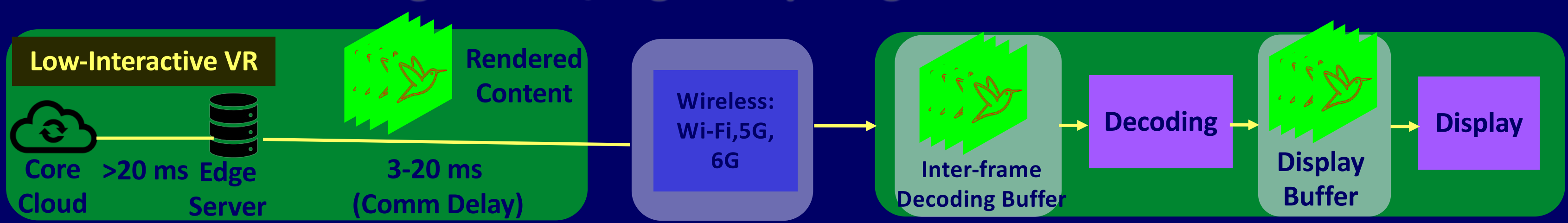


POTENTIAL SOLUTIONS

- AR/MR/High-interactive VR
  - Intra-Frame Coding & Edge Computing



- Low-interactive VR
  - Inter-Frame Coding & Cloud/Edge Computing



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LATENCY CHALLENGE 1

- **Wireless and Wireline Latency Minimization**
  - Measurements show that 5G public network latency is around 21.8 ms and 27. 4 ms
  - 5G private networks (e.g., campus networks) have a lower latency, i.e., < 10ms
  - **Solution 1:** Use specialized scheduling and resource reservation algorithms
  - **Solution 2:** Upgrade wireline networks to support high-speed wireless communication

- D. Xu, et al. "Understanding operational 5G: A first measurement study on its coverage, performance and energy consumption" ACM Sigcomm'20.
- A. Narayanan, et. al. "A first look at commercial 5G performance on smartphones" WWW'20.
- J. Rischke, et. al. "5G Campus Networks: A First Measurement Study" IEEE Access (2021).

LATENCY CHALLENGE 2

- **Trade-off between Video Encoding and Wireless Communication**
  - Video encoding can take much longer than 10 ms, e.g., as high as several hundreds of ms
  - Low compression ratio can reduce the encoding/decoding latency, e.g., intra-frame coding → require more wireless communication resources
  - Trading wireless communication resources for low latency
  - Precisely control latency by dynamically allocating wireless communication resources

LATENCY CHALLENGES 3 & 4

- **Optimal Edge Computing and Caching**
  - High-bandwidth cloud computing with GPU is expensive, e.g., several thousand dollars per month
  - Edge Computing: low cost, low latency
  - Caching can reduce computation delay, e.g., LAXR supports local activities that have significant identical contents

- **Automatic Network Slicing**
  - Automatically reserve resources for XR applications to maintain low latency

ARTIFICIAL INTELLIGENCE

X. Liu, et. al.
"Learning-based Prediction, Rendering and Transmission for Interactive Virtual Reality in RIS-Assisted Terahertz Networks."
IEEE Journal on Selected Areas in Communications (2021).

- **Motion Prediction**
  – Predict user motion and behavior to render content and plan communication resources in advance → reduce latency

- **Field-of-View Prediction**
  – Reduce rendered content volume using a small FoV rather than the 360° video

- **AI in other Research Topics**
  – Generative Adversarial Network (GAN) for video encoding
  – Wireless/wireline network resource management
  – Computer vision

MOBILITY

- LAXR: Local Area VR, AR & MR
  - Applications: VR gaming, AR/MR assistance and design, etc.
  - A small moving area
  - Intelligent communication environment + motion prediction → reliable and low-latency services

- WAXR: Wide Area VR, AR & MR
  - Frequent handoffs, e.g., VR users on a train
  - Soft handoff and trajectory prediction → allocate resources in advance

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POWER CONSUMPTION & WEIGHT

- High power consumption of Head Mounted Display due to display, computation, communication, sensing, etc. → heat

- Large weight of Head Mounted Display due to display, CPU/GPU, battery, storage, cameras, sensors, etc. →not wearable

- Solutions
  - Offload computation tasks to servers →reduce weight and power consumption
  - Wireless power transfer→ reduce battery size

    e.g., simultaneous wireless power and information transmission

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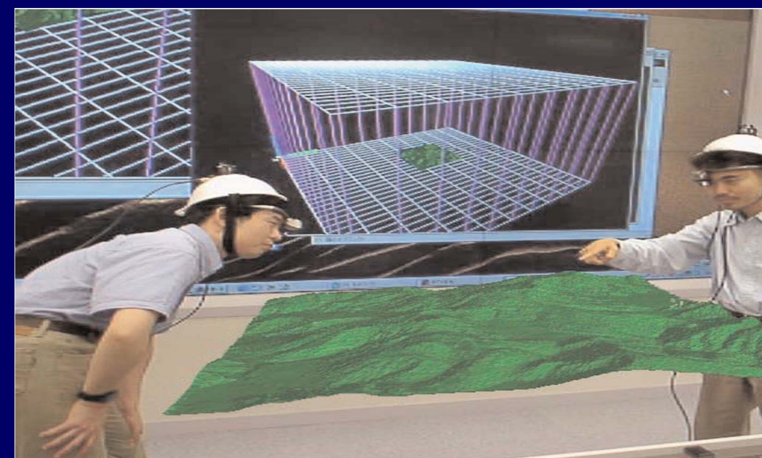
COLLABORATIVE WIRELESS XR

M. Billinghurst and K. Hirokazu.
"Collaborative Augmented Reality."
Communications of the ACM (2002).

- **LAXR:**
  - Multiple wireless XR users in a small area working collaboratively
  - Interference management
  - Caching

- **WAXR:**
  - Multiple wireless XR users remotely collaborate on a project
  - Latency and synchronization



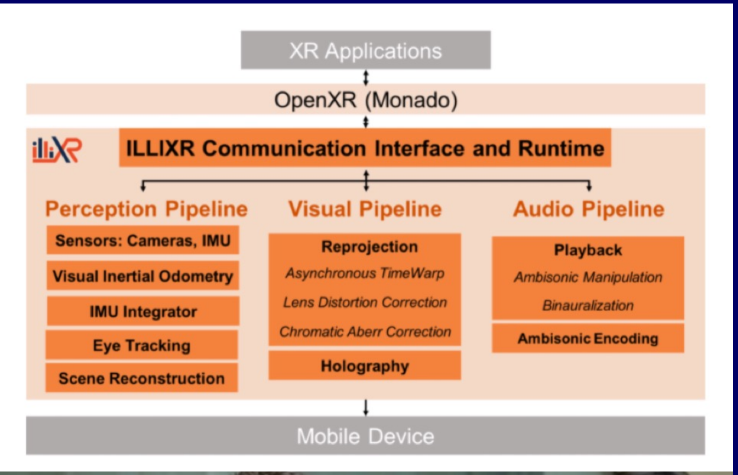
Two scientists discuss a terrain model of Japanese mountain Yakedake (Wired)

Mixed reality enables immersive collaboration for remote teams

RESEARCH TESTBEDS

M. Huzaifa, et al. "ILLIXR: Enabling End-to-End Extended Reality Research"
IEEE International Symposium on Workload Characterization (IISWC), 2021.

- Existing XR testbeds are mainly cable-supported using existing products
- ILLIXR is the first fully open source XR system and testbed
- Future research: wireless testbeds (5G, 6G, Wi-Fi) + open source XR testbeds



https://illixr.github.io

FURTHER CHALLENGES

- Security and Privacy
  - Attackers can modify augmented virtual information, e.g., road stop sign or speed limit
  - AR/MR cameras always capture users surrounding environment
  - Detect malicious information and protect users' security and privacy

- Wireless Sensing
  - mmWave and Terahertz signals can be leveraged for hand tracking, head tracking, body motion detection, etc.
  - Reduce the number of sensors on Head Mounted Displays

CONCLUSION

- XR, including AR, MR and VR, is an emerging research area that will profoundly change the way we interact with each other and the physical world
- Wireless technologies, e.g., 5G, 6G and the next generation Wi-Fi systems, will support ubiquitous high-quality XR
- Research challenges mainly lie in high data rates (> 1 Gbps) and low latency (< 10 ms)