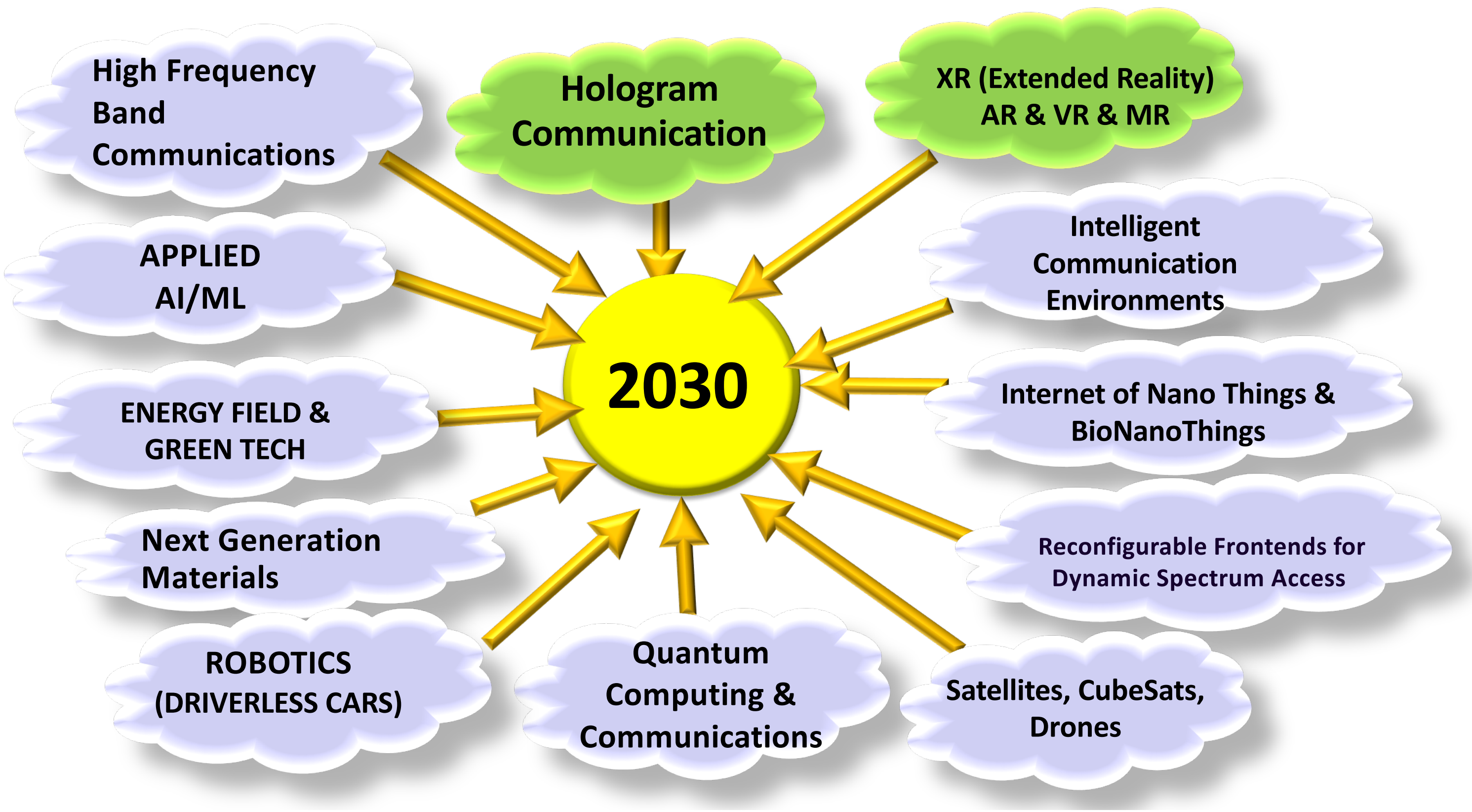
Wireless Communication Challenges for Extended (Augmented and Virtual) Reality (XR)

I.F. AKYILDIZ

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

Key Techs for the Next Decade

I. F. AKYILDIZ, A. KAK, S. NIE
"6G AND BEYOND: THE FUTURE OF WIRELESS COMMUNICATIONS SYSTEMS",
IEEE ACCESS JOURNAL, VOL. 8, PP. 133995-134030, JULY 2020.



Networking 2030 (Another Perspective)

FG-NET2030, ITU-T

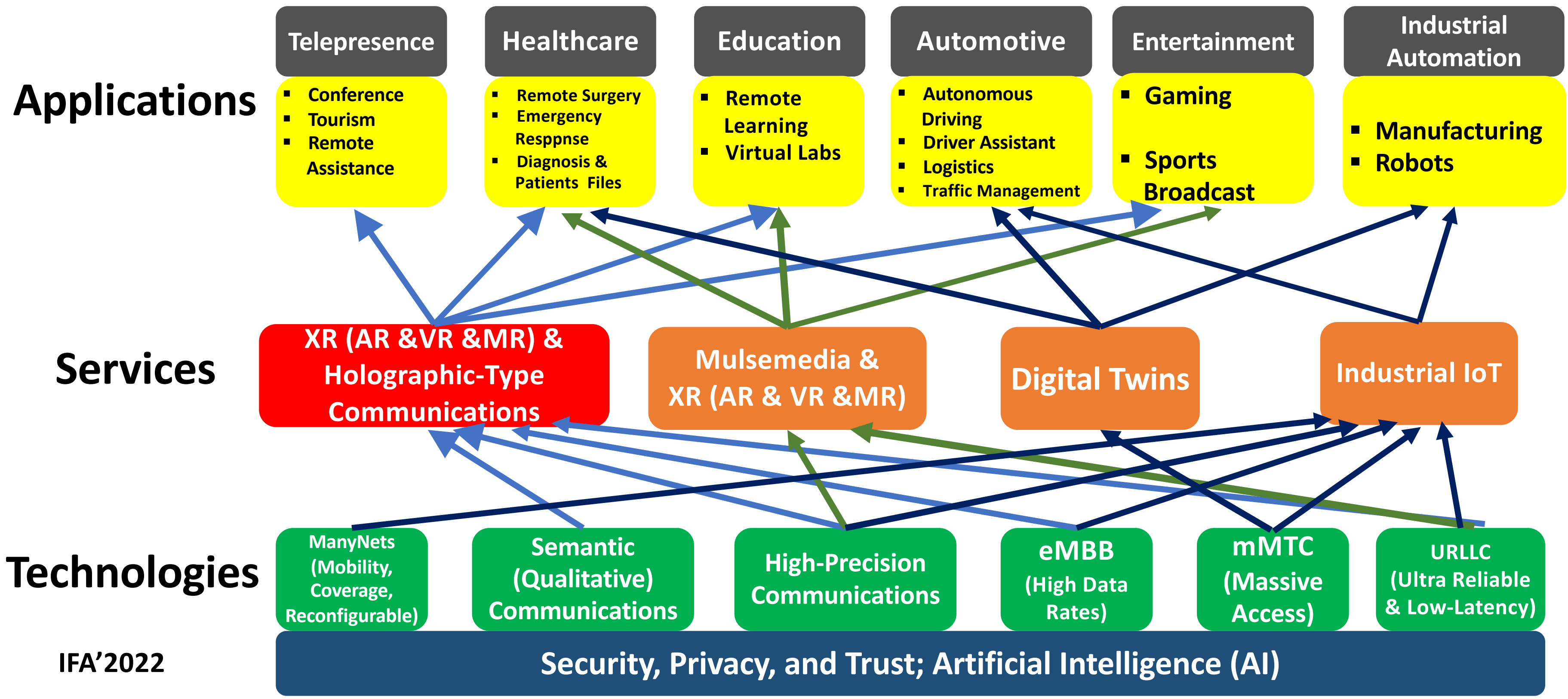
"New services and capabilities for network 2030: description, technical gap and performance target analysis"

FG-NET2030 document NET2030-O-027(2019).

FG-NET2030, ITU-T

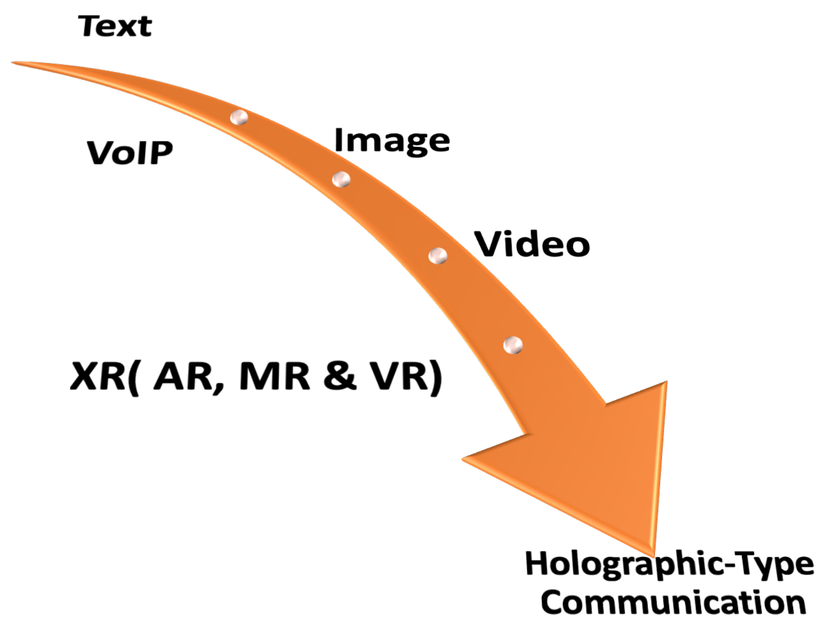
"Representative use cases and key network requirements for network 2030"

FG-NET2030 document NET2030-O-027 (2020).



Evolution

- 1990: Mobile Voice Communication
- 2000: Mobile Data
- 2010: Mobile Internet
- 2020: Mobile Things
- 2025: XR & AI/ML
- 2030: Mobile Intelligence and HTC



TAXONOMY of XR (AR, MR and VR)

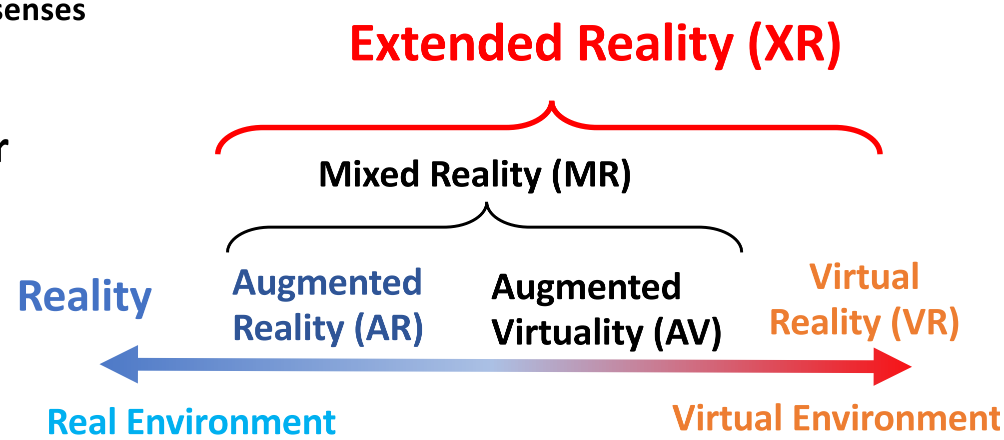
Reality:
Human perception of real objects is based on five basic senses:
Sight, Hearing, Touch, Smell, and Taste

Virtual Reality (VR):
Creating digital virtual objects to represent the same real senses and environments

XR (eXtended Reality) is an umbrella term for

- **Augmented Reality (AR)**
  - Real environment is augmented with virtual objects and information
- **Virtual Reality (VR)**
  Fully virtual environments & objects
  - A mixture of real and virtual environments
    * Low % of virtual contents → AR
    * High % of virtual contents → AV

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



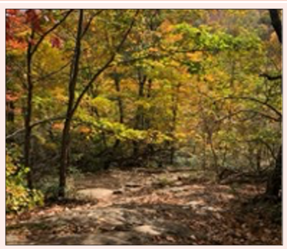
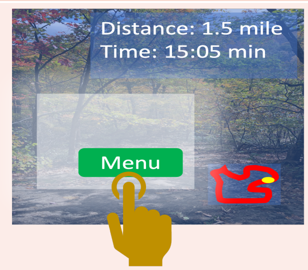
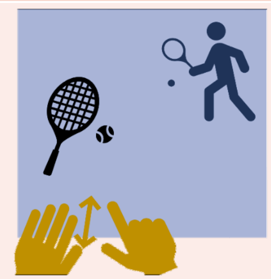
Reality-Virtuality Continuum

New technologies AI/ML, IoT, 5G/6G, make these realities possible !

Extended Reality

- **Essential part of industrial processes**
- **Its application has become fundamental to Industry 4.0**
- **Increases business efficiency, productivity, competitiveness and increases safety levels.**

Devices & Use Cases

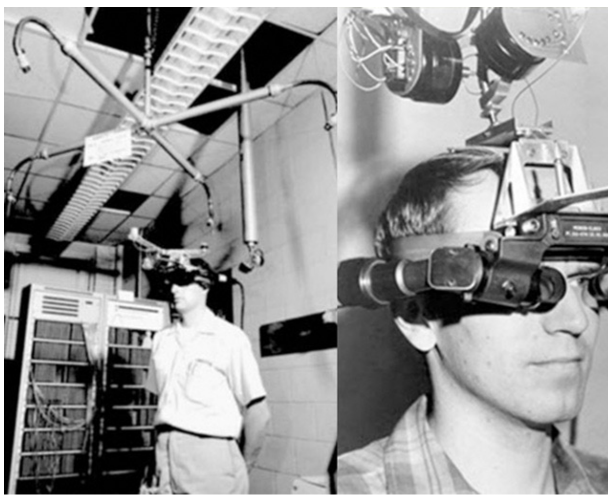
		Extended Reality (XR)		
	Reality	Augmented Reality (AR)	Mixed Reality (MR)	Virtual Reality (VR)
Display	Naked Eye/Optical Glasses	Translucent Display	Translucent Display	Occlusion Display
Display Example				
Example	 Real View of a Trail	 Augmented Virtual Map and Direction	 Interactive Virtual Contents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

Some More Simple Use Cases

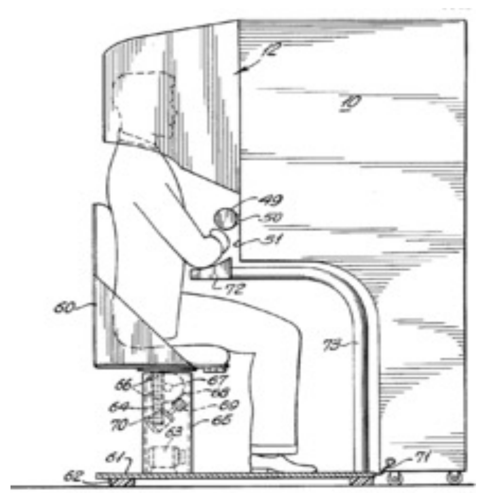
- Customer can try clothes or beauty products before buying
- How a piece of furniture looks in their living room
- A painting on the wall → reduces potential returns and improves consumer exp.
- Manufacturing → e.g., training of personnel
- Entertainment, sports, health care, tourism, education and e-commerce, etc.
- XR will attract the attention of investors and will be a booming field.

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**

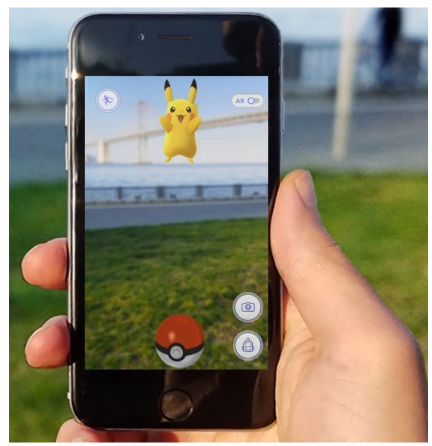
- **Wireless Solutions for XR ?**

Augmented Reality (AR)

This technology allows virtual elements to be added to the real world, such as images, sounds, videos and 3D Figures.

- **Contents**
  - **Virtual Objects: Pokemon GO**
    (allows players to locate and capture Pokémon in real places).
  - **Virtual Information: Assistance**
    (e.g., give to consumers access to relevant information about products prior to purchase)

- **Devices**
  - **Non-immersive AR: Smart devices, e.g., cell phones, iPads, computers**
  - **Immersive AR: Optical Head Mounted Displays**

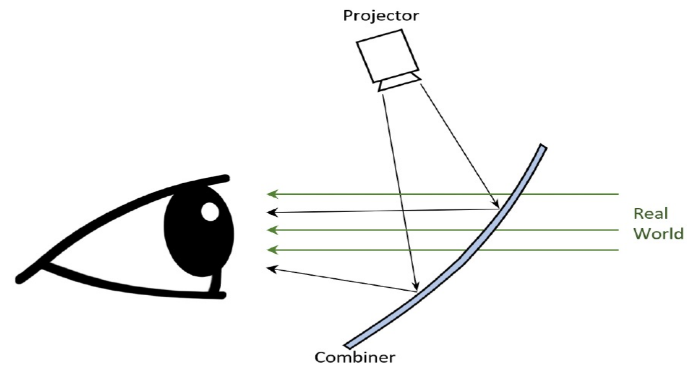


Source: vg247.com

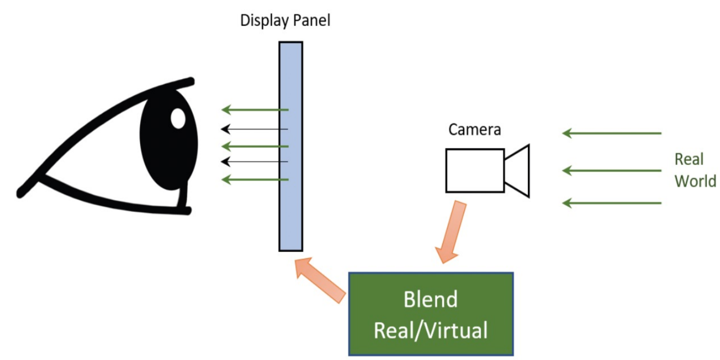
Source: assemblymag.com

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**



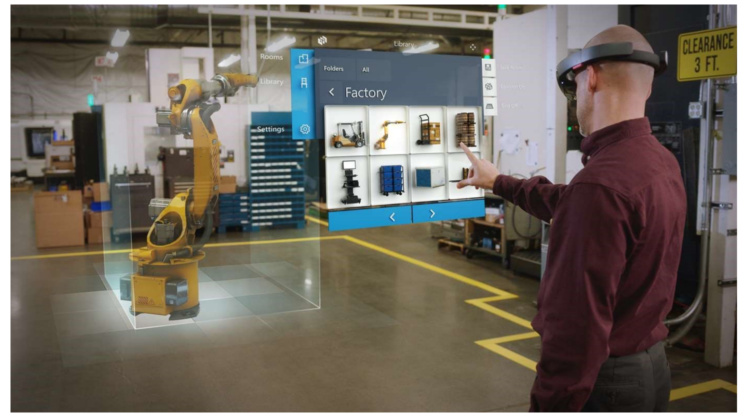
D. Wagner, L. Noui, A. Stannard,
"Why is making good AR displays so hard?", 2019

Mixed Reality (MR)

It also requires a special helmet to access and allows the user to interact with virtual elements in real time, without losing sight of the world around them.

- **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)**



Virtual Reality

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

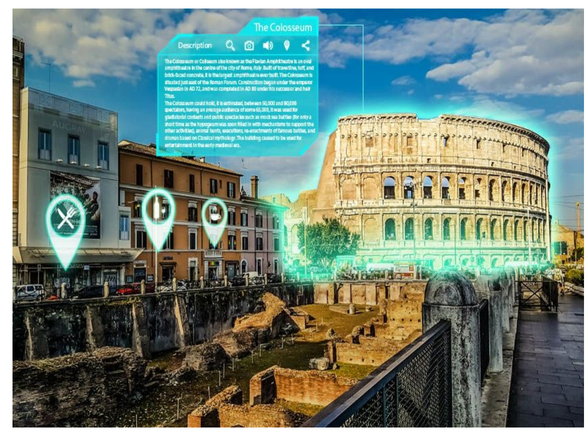
Source: computingnews.com

Source: archdaily.com

HTC vive

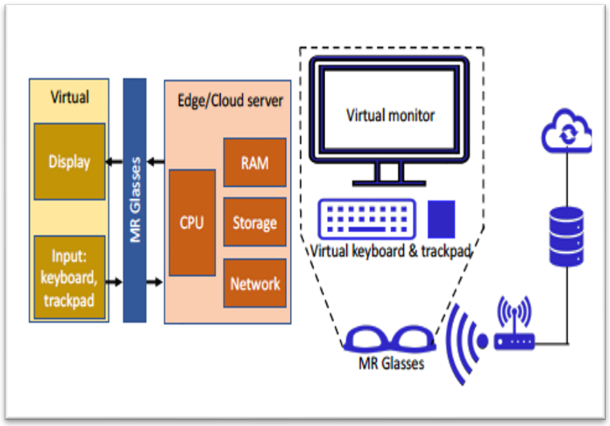
Use Cases: AR

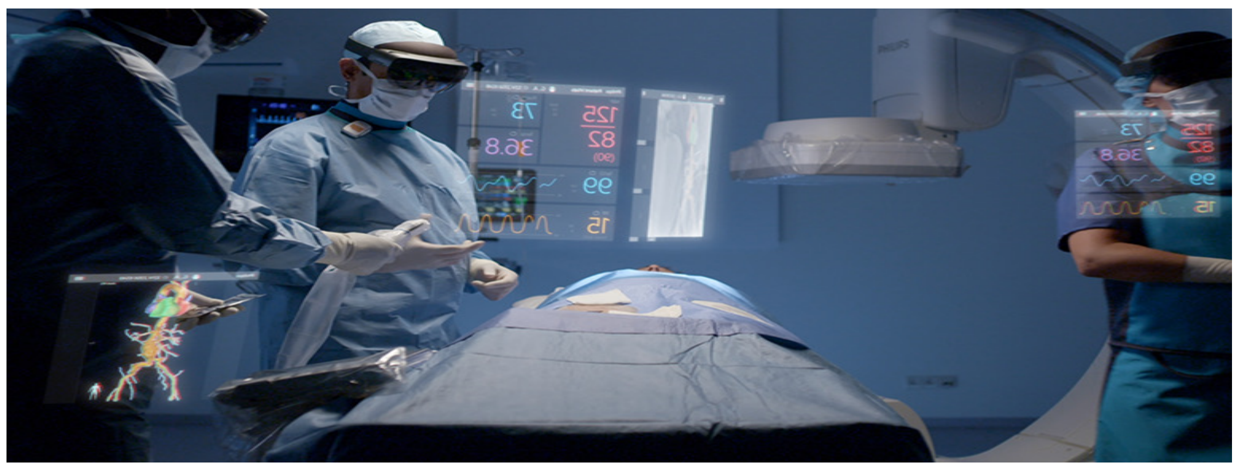
- Sports
- Automotive
- Real Estate
- Tourism



Use Cases: MR

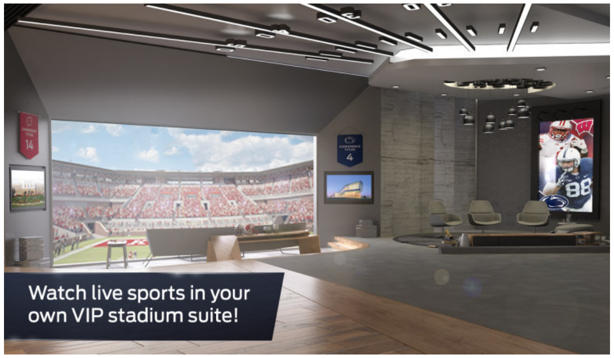
- **Virtual Computing Environment**
  - **Virtual computer**
  - **3D Design**
  - **Healthcare**





Use Cases: VR

- Personal Movie Theater
- Sports
- Gaming



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	–







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 mm-Wave 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

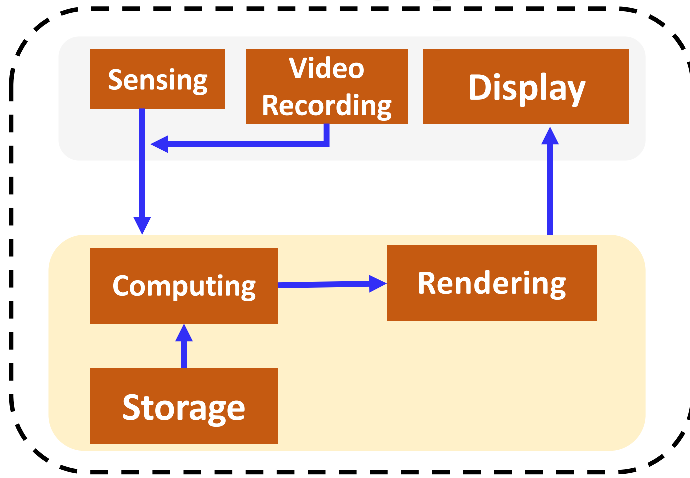
- Applications are pre-installed in XR headsets/glasses using wireless/wired communications
- Otherwise self-sustained
- Pros: low latency, not tethered
- Cons: very limited functionalities due to limited storage, energy, and computing resources

RENDERING:

A process to prepare the display of virtual contents.

A rendered graphic; it automatically changes position on the display as the user turns to face toward or away from the known object, or tilts their head up or down with respect to it.

XR Headsets/Glasses



Not the focus of this talk!

Server-Supported Architecture

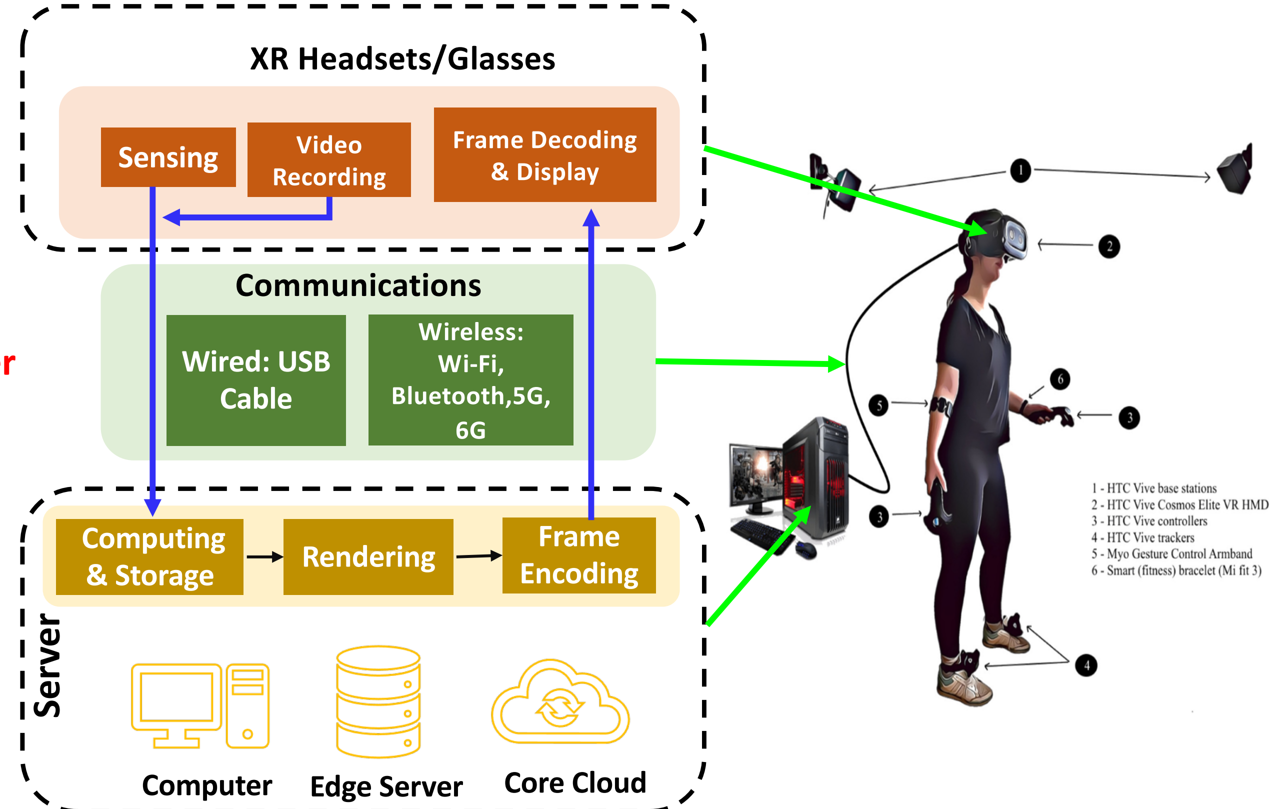
- Computing and storage are offloaded to servers,

  e.g., computers, edge and cloud servers

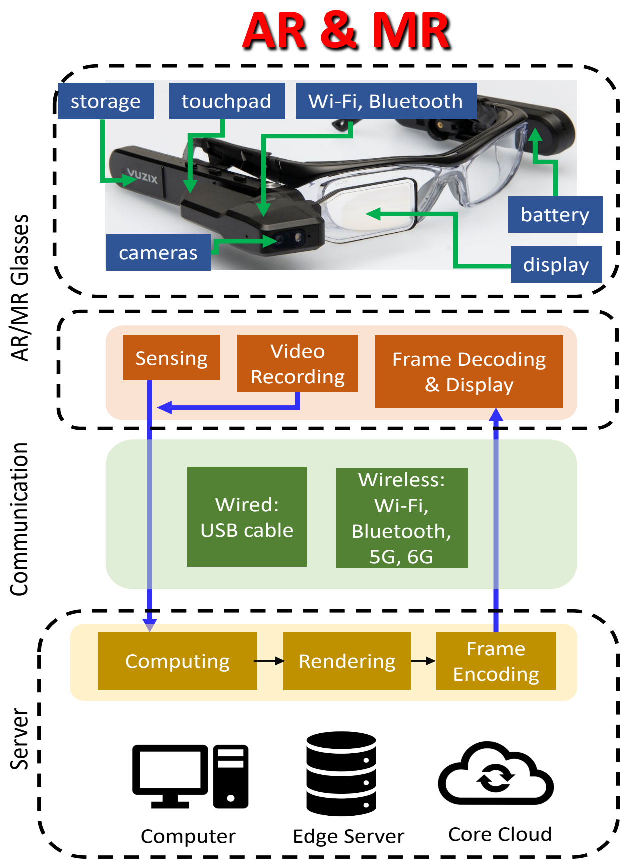
- Pros:
  - i) reduce size, weight, and power consumption of headsets
  - ii) support complex applications

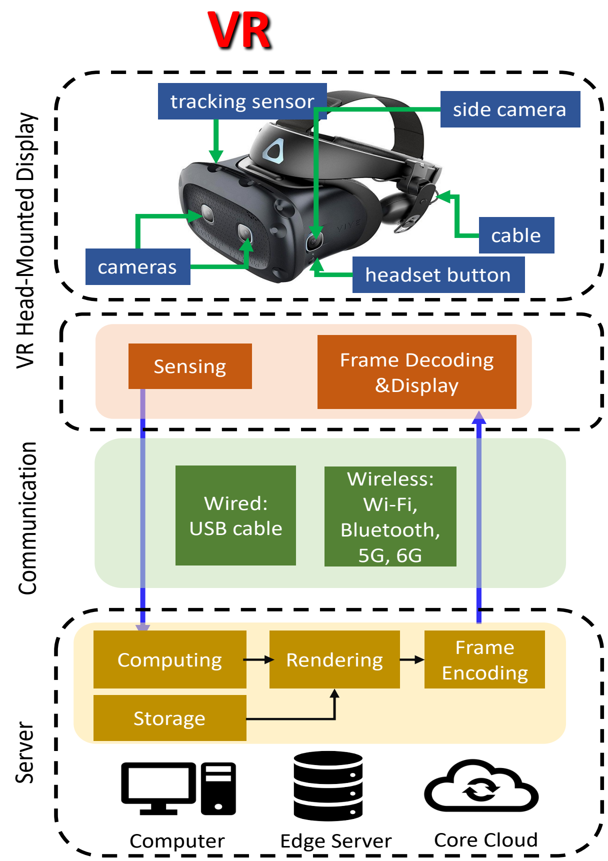
- Cons:

  require wired/wireless communications



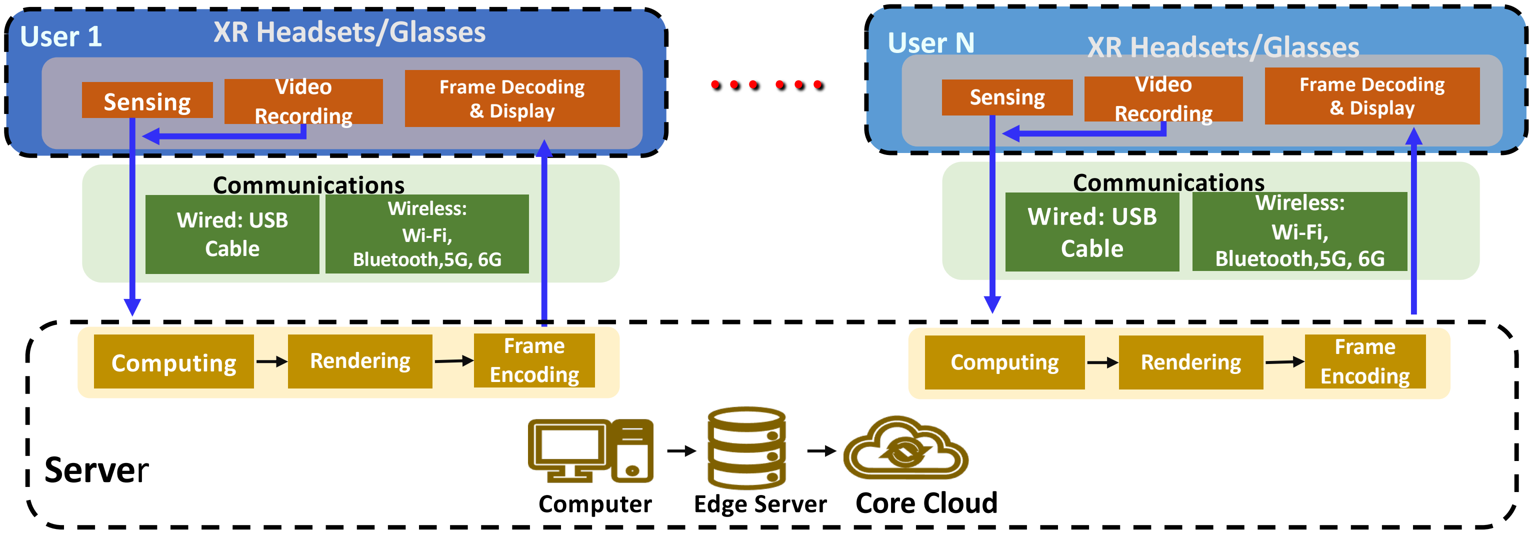
Summary: AR, MR & VR System Architecture





AR 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)

Technical Requirements

- 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 (UL & DL)
  - Future Haptic (Touch) communication (in progress),
    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

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 Research 123 (2021): 289-301.

	Sight	Hearing	Touch	Smell	Taste
Holographic-Type Communication	✓	✓	✓	✓	✓
XR (AR, MR & VR)	✓	✓	✓		
Haptic Communication	✓	✓	✓		
Video	✓	✓			
Image & Text	✓				
Audio		✓			

Technical Requirements

	Video	VR	MR & AR	Holographic-type Communication
Data Rates	35~100Mbps	35Mbps~15 Gbps	35Mbps~15 Gbps	1~10Tbps
Latency (high to low)	15~35ms	~20ms	~10ms	<1ms
Synchronization	Audio/Video	Multiple Tiles	Multiple Tiles	Thousands (views/senses)
Devices	Smart Devices/Computers	Head-Mounted Display	Smart Glasses	Naked Eyes/HMDs

- **XR & Hologram-based applications will place significant demands on networking infrastructure → NOT supported today !**

Computation of Data Rates and Latency

- **Data Rate** = Resolution $\times$ Refresh Rate $\times$ Bits of color (8 or 12) $\times$ 3 (RGB) $\times$ 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) $\times$ PPD $\times$ Horizontal Degree (from FoV) $\times$ PPD
- **Field-of-View (FoV):**
  Angle of the maximum area that we can observe ($\approx$130° per eye and $\approx$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

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 $\times$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° $\times$ 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° $\times$ 110°): 428.2 Gbps → use a 300:1 compression rate: 1.4 Gbps**

Latency

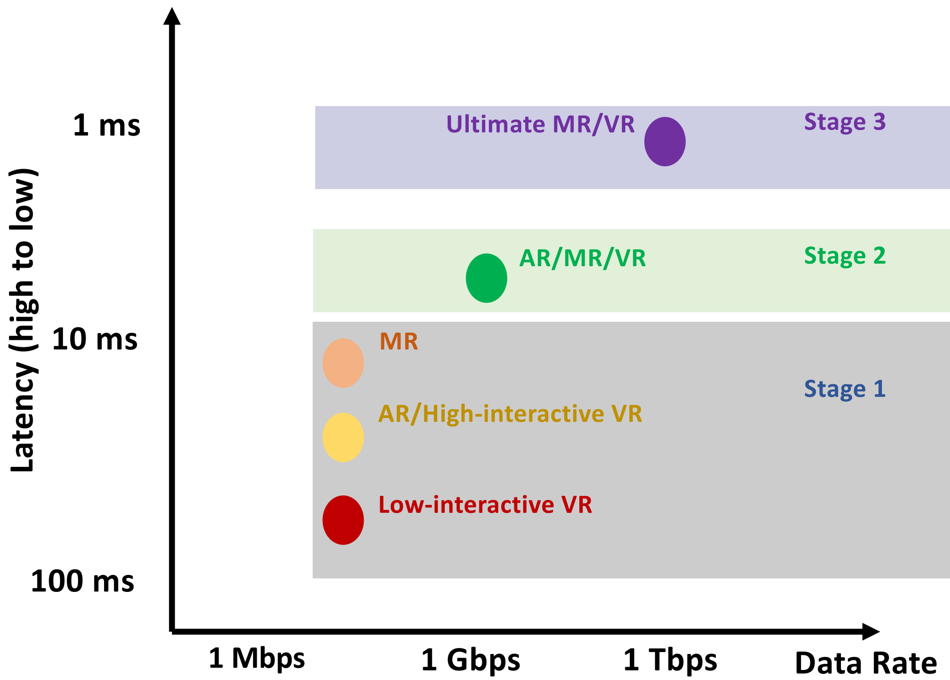
- **Applications require different latencies**
  App1: **AR, MR, and high-interactive VR (e.g., gaming)**
  App2: **Low-interactive VR (e.g., personal movie theater)**

- **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.**

Future: 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



XR Research Directions

Communication & Networking

- High Data Rates (Tbps) with Low Latency Communication → 6G and beyond
- Semantic Communication Networks
- High-precision Communication Networks
- Federated Networks & AI/ML Empowered Networks

XR Server and User Devices

- Mulsemedia Transmission and Synchronization
- User Motion Prediction
- 360-degree video capture, synchronization, and display

Edge Computing

- Lightweight Edge and on-device Processing
  - Due to the extremely low latency requirements, data processing must be done at the edge and on user devices → Low-complexity data processing algorithms
- High-quality XR Data Compression and Decompression
- High Processing Power: Real time processing

xRe Project:

Enabling Ubiquitous Wireless XR with Extremely High QoE
2021-2025

High Data
Rates &
Latency

New IP Protocol Design

Semantic Communication

Federated Networks & AI/ML Empowered Networks

MOBILTY EFFECTS &

COLLABORATIVE WIRELESS XR

EDGE INTELLIGENCE

Power Consumption & Weight Reduction

TESTBED

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TESTBED

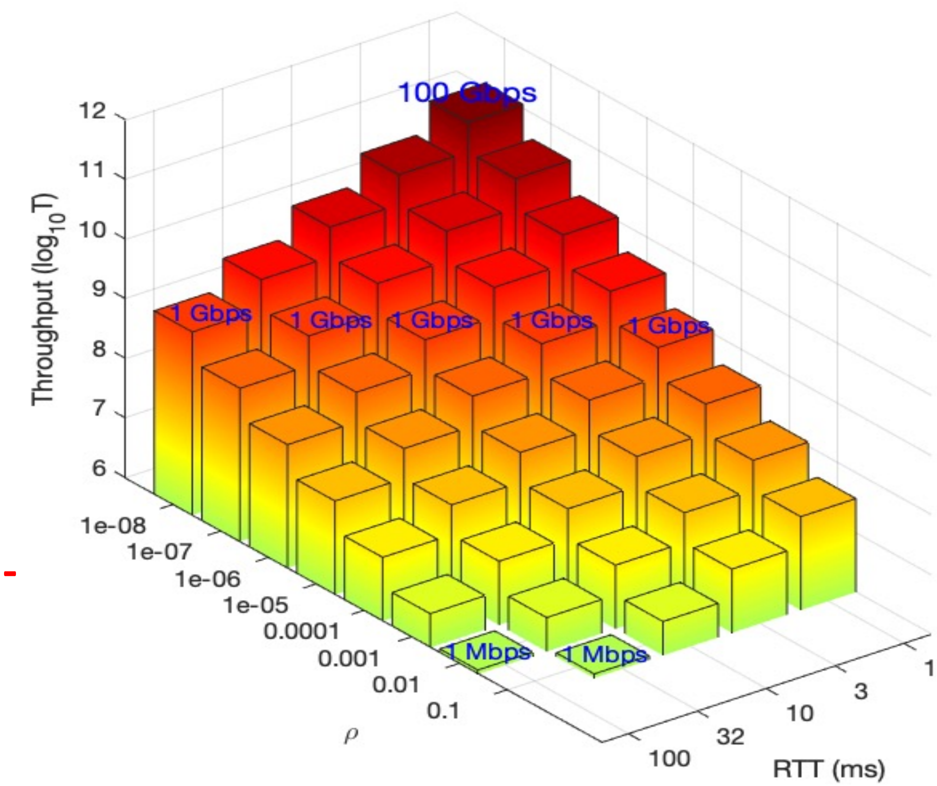
Data Rates: Today's Internet Performance

- **TCP Throughput (Cerf-Kahn-Mathis Equation)**

$$T \leq min(BW, \frac{Window\ Size}{RTT}, \frac{MSS}{RTT} \times \frac{1}{\sqrt{\rho}})$$

- BW **is the bandwidth**
- RTT **is the Round Trip Time**
- MSS **is the Maximum Segment Size, and**
- ρ **is the packet loss**

- **Assume infinite BW (Broadband), infinite Window Size: It requires 10^{-8} packet loss (Ultra-high Reliability) and 1 ms RTT (Ultra-low latency) to achieve 100 Gbps throughput →**
- **cannot be achieved by today's internet**



How to deal with High 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

High 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, C. Han, Z. Hu, S. Nie, and J. M. Jornet,
"TeraHertz Band Com: An Old Problem Revisited and Research Directions for the Next Decade",
IEEE Transactions on Communications, 2022.

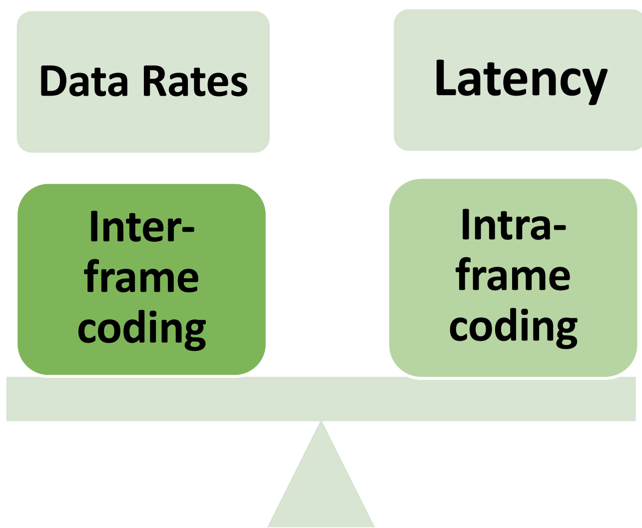
- C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I.F. Akyildiz,
  "A New Wireless Communication Paradigm through Software-controlled Metasurfaces",
  IEEE Communications Magazine, vol. 56, no. 9, pp. 162-169, September 2018.

- Optimal 6G and Beyond wireless system design
  - mmWave, Terahertz Band Communication
  - Optimal resource allocation
  - Co-design of sensing, communication and intelligence

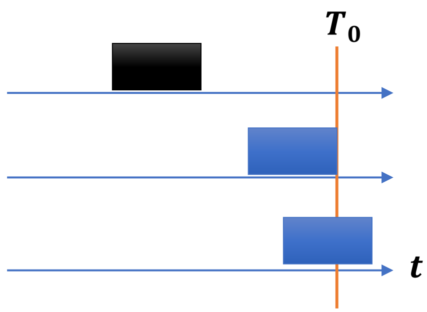
- Reconfigurable Intelligent Surfaces in unreliable/blocked environments
  - Adaptive beamforming considering user motion and wireless environment

Latency vs Data Rates

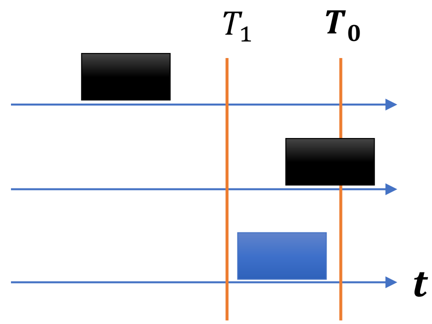
- Intra-frame Coding
  - Compression in a single frame
  - Low compression rate (require high data rates) → low latency
- Inter-frame Coding
  - Compression among multiple frames (buffer frames)
  - High compression rate (require low data rates) → long latency



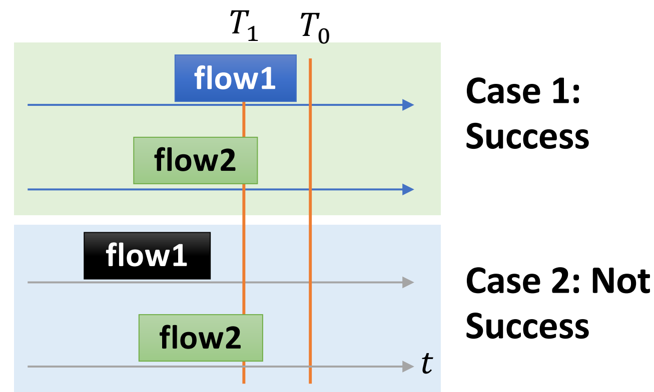
Precise End-to-End Latency Control



In-time Guarantee:
Packets delivered on or before a deadline



On-time Guarantee:
Packets delivered between a bounded time interval



Coordinated Guarantee:
Packets of two or more flows arrive in a coordinated in-time/on-time guaranteed way

- **XR data size is huge → Large Buffer size at the destination to synchronize multiple packets and multiple senses**
- **Packet need to be delivered precisely at the scheduled time to reduce the buffer size and computation burden at the destination**
- **Existing Best Effort transmission cannot meet the requirements**

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2021-2025

High Data Rates & Latency

New IP Protocol Design

Semantic Communication

Federated Networks & AI/ML Empowered Networks

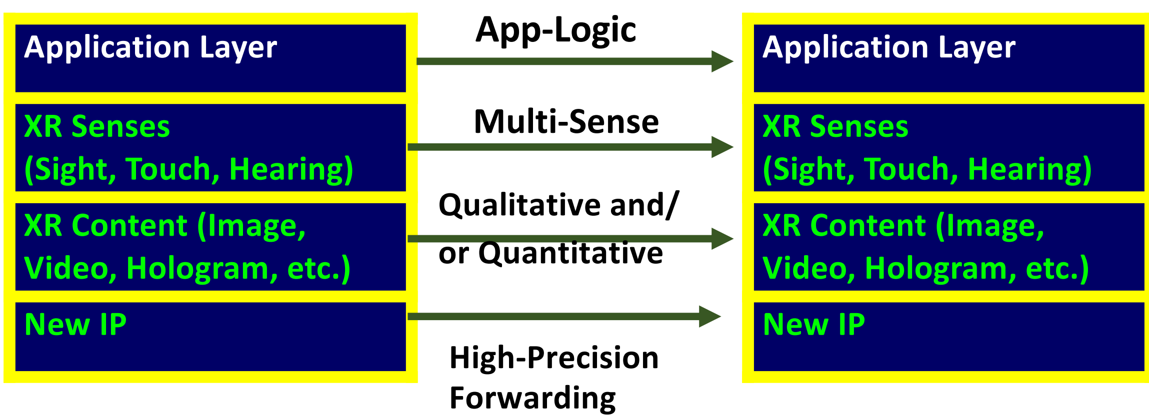
MOBILTY EFFECTS & COLLABORATIVE WIRELESS XR

EDGE INTELLIGENCE

Power Consumption & Weight Reduction

TESTBED

New Protocol Stack for XR Communications



- **New IP: A new network protocol to design network architecture, framework and infrastructure, including:**
  - **Semantic Communications**
  - **High-Precision Latency Control**
  - **Free-Choice Addressing: allows applications to use any addressing mechanism instead being constrained to IPv4 or IPv6 addresses as the only option**

Networking Streaming Protocols

- **Over-the-top (OTT) Multimedia Streaming → best solution to transmit (2D, 3D, VR, HOLOGRAM) over the Internet**

- **TCP-based Solutions**
  - **Real-Time Media Protocol (RTMP) → Splitting streams into fragments**
  - **HTTP Adaptive Streaming (HAS) → Segments on the APP layer, encoding the stream at different quality levels and temporally splitting them into segments of predefined duration and space**

- **UDP-based Solutions**
  - **Web Real-Time Communication (WebRTC)**
  - **Quick UDP Internet Connections (QUIC)**

Retransmission in XR Networks to Reduce Latency

- Retransmission is used in TCP when a packet is lost or not successfully received → increase latency and bandwidth requirement
  - e.g., if latency requirement is smaller than 1ms, any retransmission will increase the latency significantly

- Avoid retransmission → what causes packets loss and error?
  - Congestion → Drop all the packets
  - Transmission error → Correction or Retransmission

- Potential Solutions:
  - (Networking) Drop part of the packets → Semantic communication and packet wash

  - (User End) Error detection and correction using machine learning algorithms

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2021-2025

- High Data Rates & Latency
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- MOBILTY EFFECTS & COLLABORATIVE WIRELESS XR
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Quantitative Communication vs Semantic Communication

Q. Zhijin, X. Tao, J. Lu, and G. Y. Li.
"Semantic communications: Principles and challenges."
arXiv preprint arXiv:2201.01389 (2021).

- Quantitative Communication: what is received = what is sent
  - Every bit should be correctly received
  - Errors need to be detected and corrected
  - Use cases: financial transactions, user personal information

- Semantic (Qualitative) Com: what is received = what is meant to send
  - Packets with small importance value can be dropped
  - Importance value can be determined by entropy

Recent Contributions to
The Mathematical Theory of Communication

Warren Weaver

September, 1949

Semantic Communications

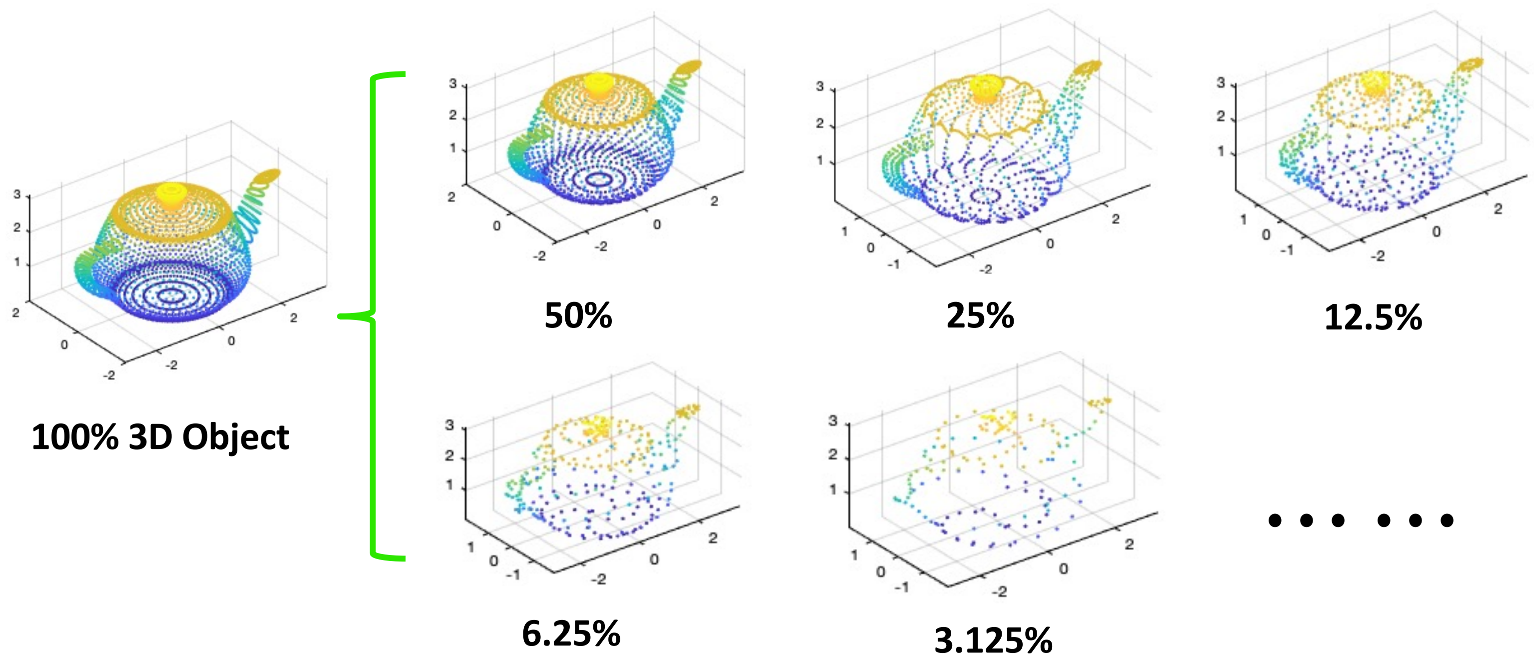
W. Weaver,
"Recent contributions to the mathematical theory of communi
ETC: a review of general semantics(1953): 261-281.

Claude Shannon

Warren Weaver

- **A long-standing problem back to the age of Shannon**
- **Three levels of communication problems**
  - **Technical Problem: How accurately can the symbols of communication be transmitted? (Shannon's Mathematical Theory)**
  - **Semantic Problem: How precisely do the transmitted symbols convey the desired meaning?**
  - **Effectiveness Problem: How effectively does the received meaning affect conduct in the desired way?**

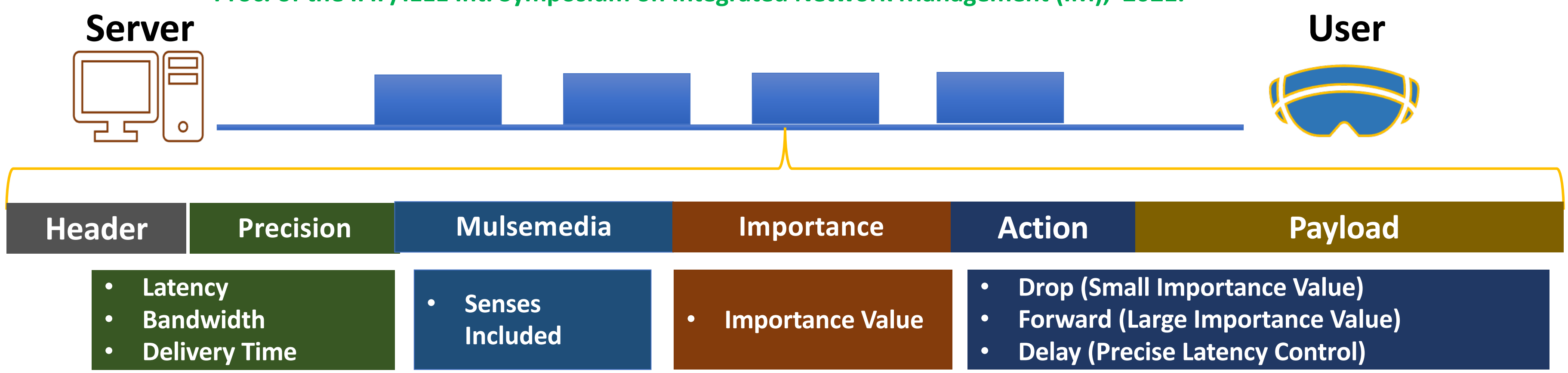
Semantic Communication & Layered Content



- 3D data can be divided into layers with different quality
- Adaptively transmit at the source, drop in the network, and render at the destination

Semantic Communication & Packet Wash

L. Dong, and A. Clemm.
"High-Precision End-to-End Latency Guarantees Using Packet Wash."
Proc. of the IFIP/IEEE Int. Symposium on Integrated Network Management (IM), 2021.



- Packet Wash: in presence of network congestion, drop packets that do not significantly affect the QoE (Quality of Experience)
- Drop packets with small importance values instead of dropping all the packets
- Importance value of survived packets should be increased

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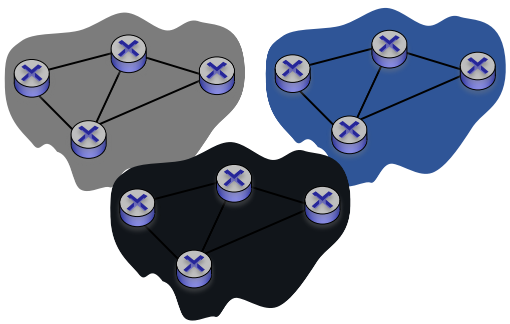
Federated Networks

- The number of private networks are growing significantly, e.g., campus networks, industrial networks, etc.
- XR networks can be implemented starting from private networks → available resources & low latency
- Public network backbone may not be required → global networks evolve into federated networks
- How to set a consistency policy for different private networks?



AI-empowered Network Prediction and Adaptive Control

- J. P. Vasseur
  “Towards a Predictive Internet”
  Cisco Report 2021.
- U. Chunduri, A. Clemm, and R. Li.
  "Preferred Path Routing- A Next-Generation Routing Framework Beyond Segment Routing."
  IEEE Global Communications Conference (GLOBECOM)., 2018.

- **Predict network traffic and congestion in order to adaptively obtain the optimal path**
- **Provide learning ability to networks to automatically allocate resources and control streaming rate**
- **Towards a predictive Internet**

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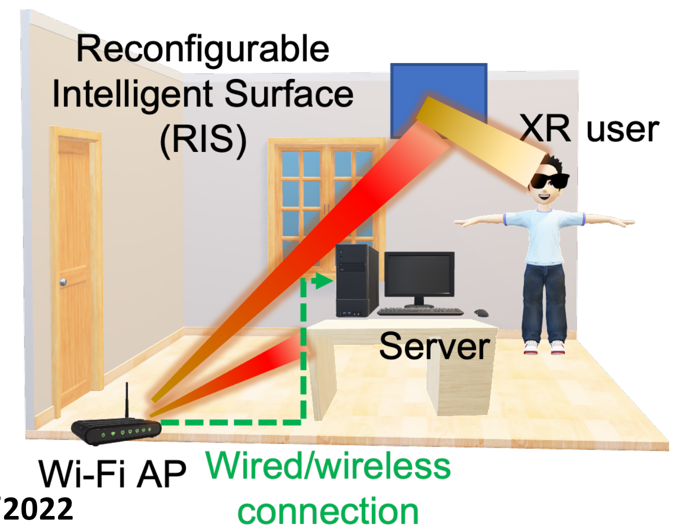
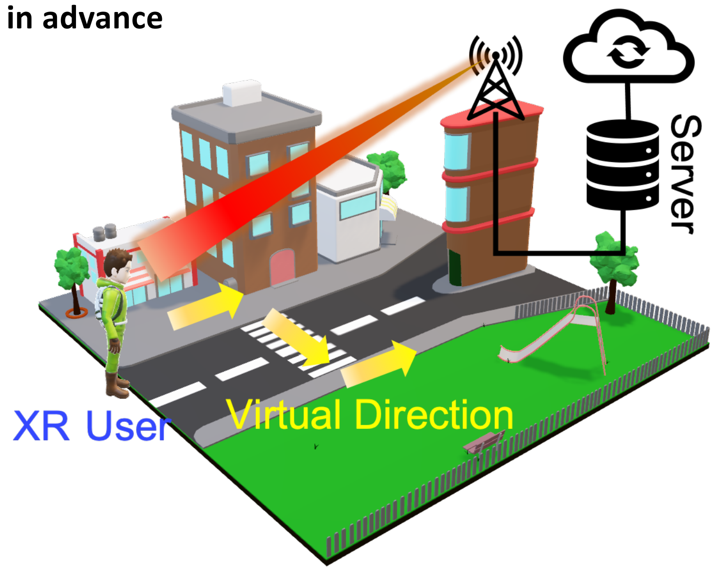
HOW TO DEAL WITH MOBILITY?

- 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



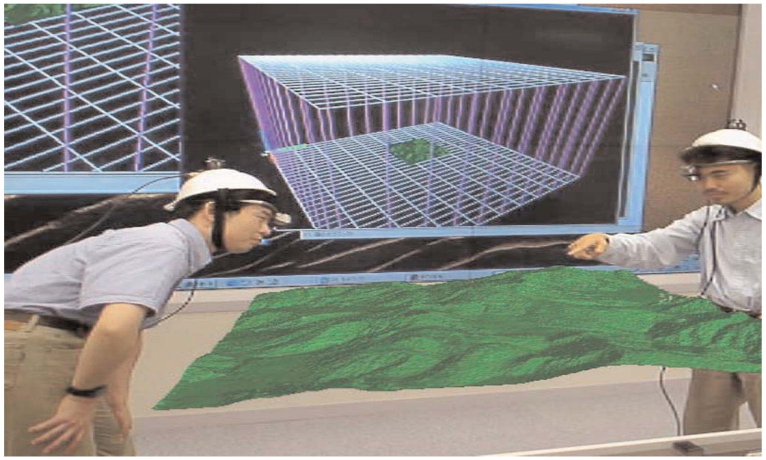


Collaborative Wireless XR

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

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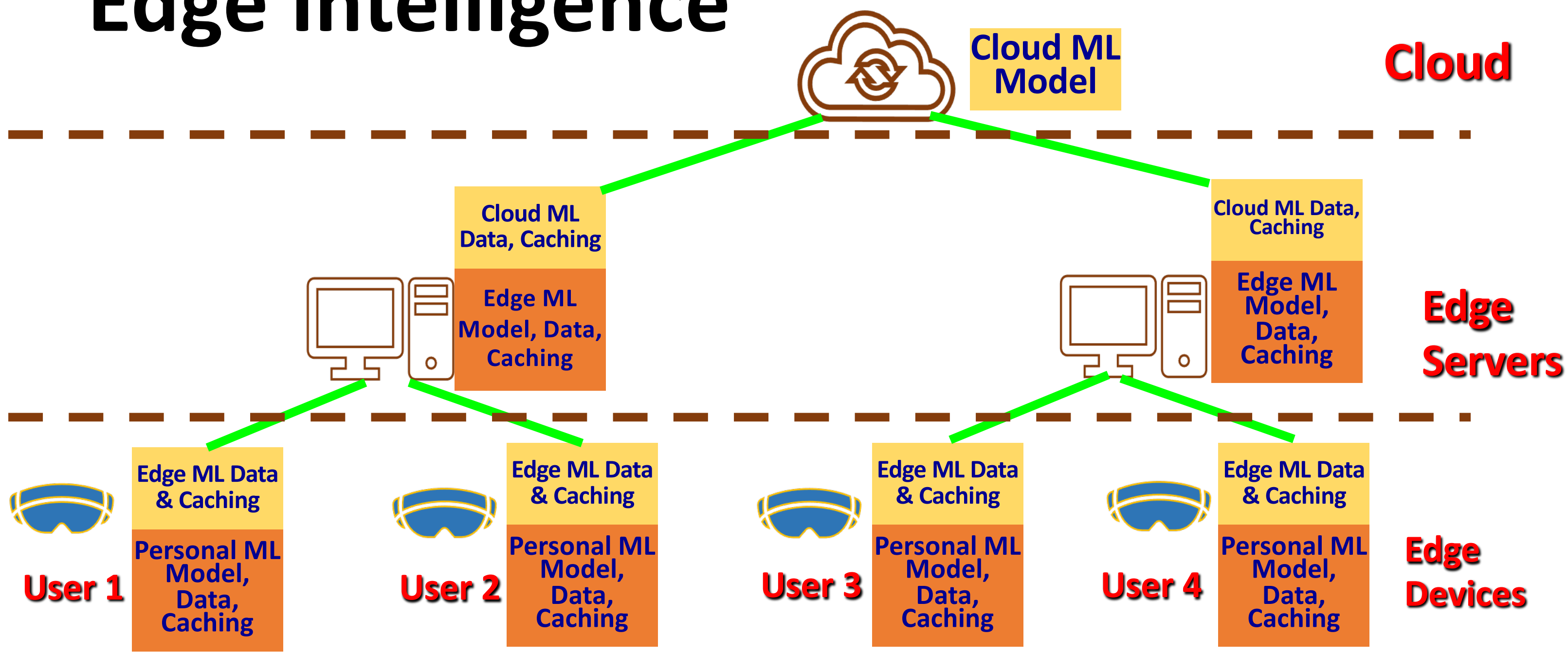
Edge Intelligence



- Edge Device Intelligence (serve a single user): Personalized ML for sensing, computing and rendering → Low-complexity, low latency
- Edge Server Intelligence (serve multiple users in a small area): local area ML for computing and networking → Environment-specified, low latency

Edge Intelligence in XR Systems: XR CONTENT GENERATION

D. Xu, et al.
"Edge Intelligence: Empowering Intelligence to the Edge of Network."
Proceedings of the IEEE 109.11, pp. 1778-1837, 2021.

- **Edge Devices:** **Cameras & Sensors**
- **Data Aggregation Intelligence:**
  With edge intelligence, sources can more efficiently compress or select useful data (e.g., semantic)

Edge Intelligence in XR Systems: XR User Devices

D. Xu, et al.
"Edge Intelligence: Empowering Intelligence to the Edge of Network."
Proceedings of the IEEE 109.11, pp. 1778-1837, 2021.

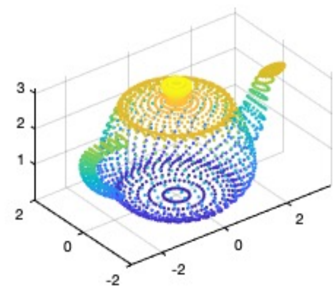
- **Edge Devices**: displays, sensors & actuators
- **Intelligence of Error Correction, User Behavior Prediction and QoE Improvement:**
  Edge intelligence can be used to correct errors or improve the quality of experiences based on predictions of users' motion and limited received data

Edge Intelligence in XR Systems: XR Networking

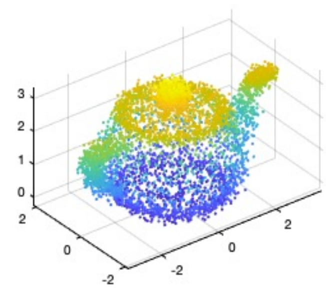
D. Xu, et al.
"Edge Intelligence: Empowering Intelligence to the Edge of Network."
Proceedings of the IEEE 109.11, pp. 1778-1837, 2021.

- Edge Servers
- Intelligence of computation offloading, caching, inference and training:
  - Optimal policies to determine computation location: edge devices, edge servers, or cloud servers
  - Caching of computation models, results, and frequently accessed data
  - Inference of network status and user behavior
  - Training efficient AI model based on limited aggregated data

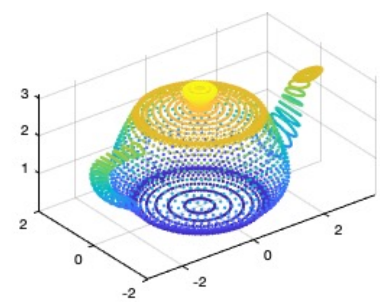
Example of Edge Intelligence: AI-empowered Error Detection and Correction



50% XR Data



Received XR Data with Noises



100% XR data

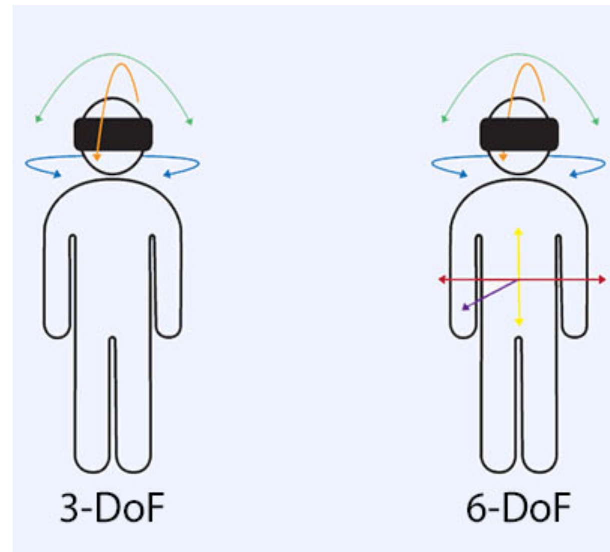
- **Can we reconstruct the original XR object with packet losses, noises and errors?**
- **Potential solutions → Machine Learning algorithms, esp. Generative Adversarial Networks (GAN)**

AI-empowered Prediction at the User End

- **Determine the Bandwidth that are wasted on contents that are never viewed**

- **User Motion Prediction (6-DoF)**
  - **User sends 6-DoF (Degree of Freedom) data to edge servers**
  - **Edge servers perform short-term prediction**
  - **Only content in the predicted FoV (Field of View) will be transmitted**

- **Challenges:**
  - **6 DoF movement prediction is challenging**
  - **Prediction error need to be addressed**



Source: virtualspeech.com

Destination QoE-Aware Design

- Leverage the characteristics of human visual perception to benefit the design of compression/computing/networking
  - e.g., Visual attention information of XR data: human eyes pay different attention to different information
  - e.g., face is one of the visual attention information about people

- Geometry texture masking effect
  - tolerance of human eyes to geometry distortion
  - better ability to tolerate geometry noise in complex regions than in geometrically smooth regions

- Fluidity of displaying 3D information at end users
  - users may prefer temporary reduction the video quality to avoid momentary disruption of video playback

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Power Consumption & Weight Reduction

- 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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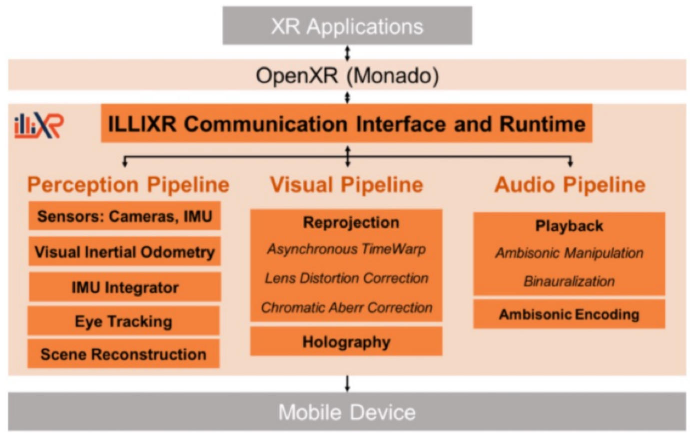
Research Testbeds

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

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)