14TH ITU ACADEMIC CONFERENCE

ITU KALEIDOSCOPE

ACCRA 2022

METAVERSE: Challenges for Extended Reality and Holographic-Type Communication in the Next Decade

7-9 December 2022
Accra, Ghana

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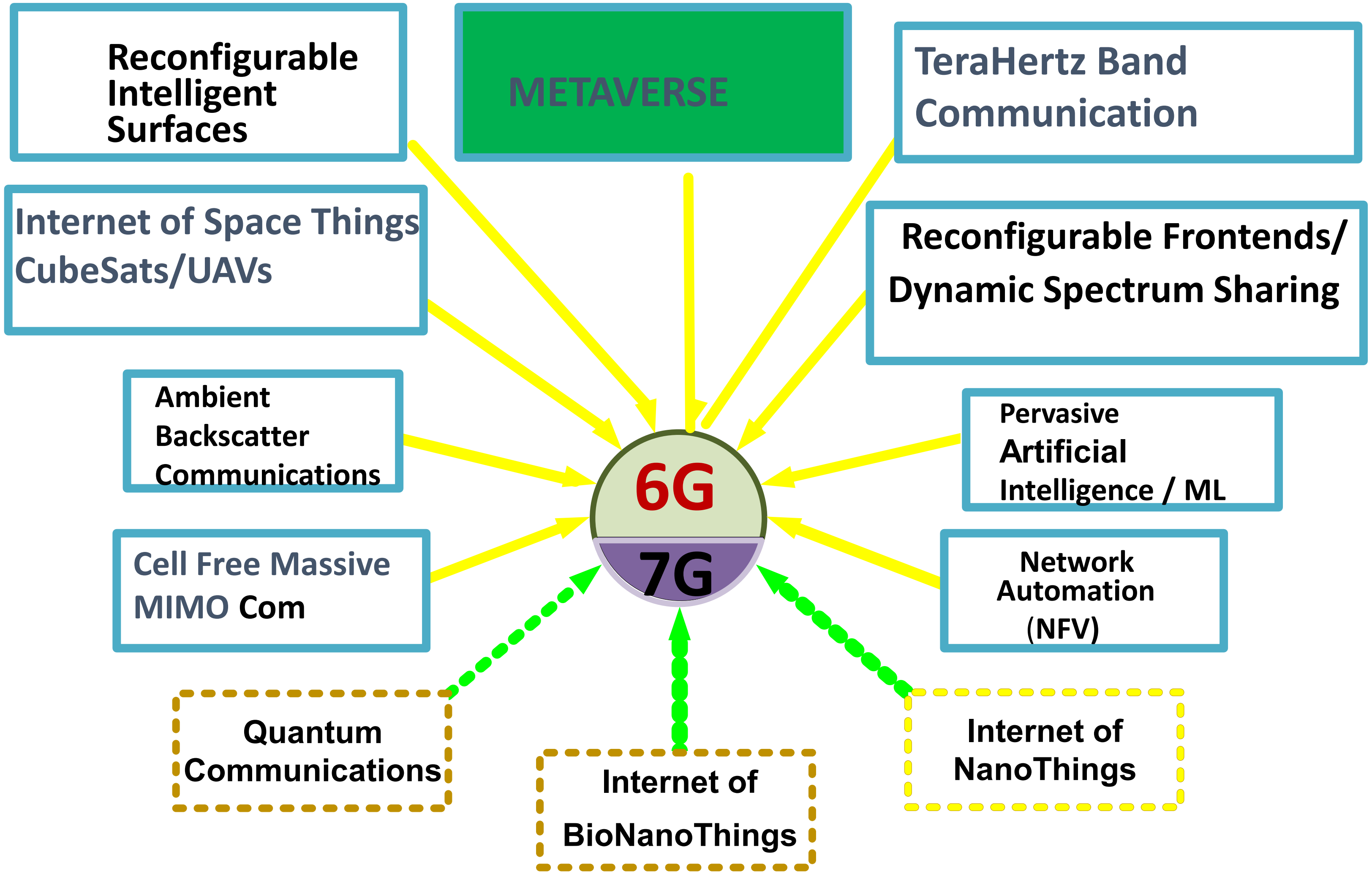
Truva, USA, and Editor-in-Chief of ITU Journal on Future and Evolving Technologies (ITU J-FET)

ITU KALEIDOSCOPE ACCRA 2022

Key Enabling Technologies for 6G and BEYOND

I. F. Akyildiz, A. Kak, S. Nie
"6G AND BEYOND: THE FUTURE OF Wireless Communication Systems",
IEEE Access Journal, Vol. 8, pp. 133995-134039, July 2020.

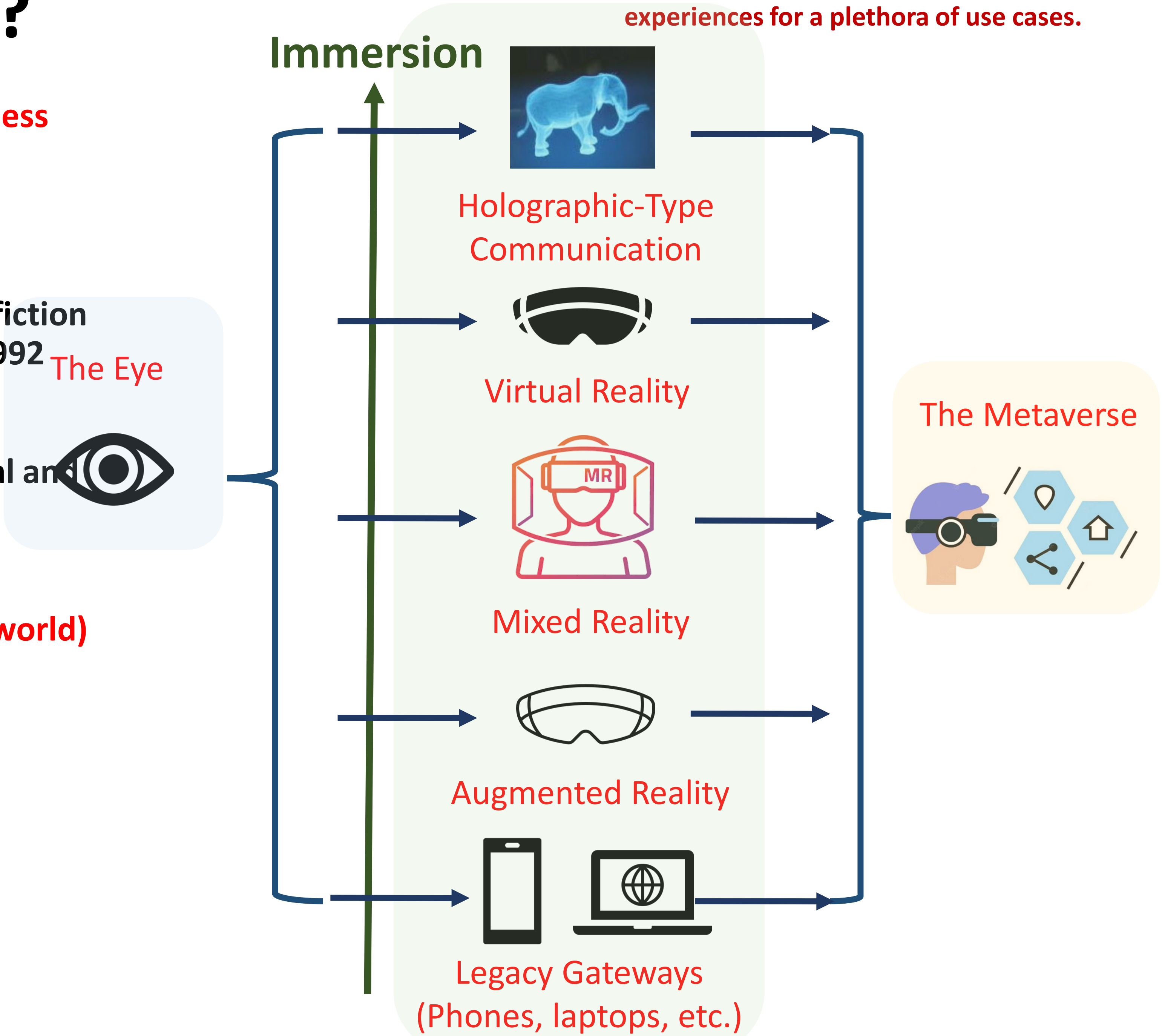


What Is Metaverse?

I.F. Akyildiz, H. Guo and R. Dai,
"Entering the Metaverse through 6G Wireless Communication Systems",
Submitted for publication in Oct. 2022.

XR and HTC provide truly immersive experiences for a plethora of use cases.

- **"METAVERSE" (META= BEYOND) and (VERSE=UNIVERSE) originated in the science fiction novel "Snow Crash" by Neal Stephenson in 1992**
- **Metaverse is a network of connecting physical and virtual world seamlessly.**
- **(No separation between digital and physical world)**
- **Realized thanks to the convergence of key emerging technologies such as**
  - **XR (VR, AR, MR)**
  - **HTC**



Metaverse Three Pillars

Metaverse Worlds (M-WORLDS)

- Work Productivity
- Interactive Gaming & Learning
- E-Commerce; Real Estate
- Fashion; Shopping; Tourism etc.

- Decentraland
- Robbox
- Somnium Space
- Second Life
- Cryptovoxels
- WorldWideWebb
- Horizon Worlds
- Gather
- Substrate
- Epic Games
- NFT Worlds

* XR Reality

(AR/VR/MR)

* HOLOGRAPHIC-TYPE COMMUNICATION

Web3.0

- Decentralized & Autonomous
- Heavily based on AI/ML
- Blockchain-based Technologies
- Cryptocurrency Enabled
- Intelligent and Adaptive Apps
- Semantic Technologies

Metaverse Market

Virtual-Asset Economy

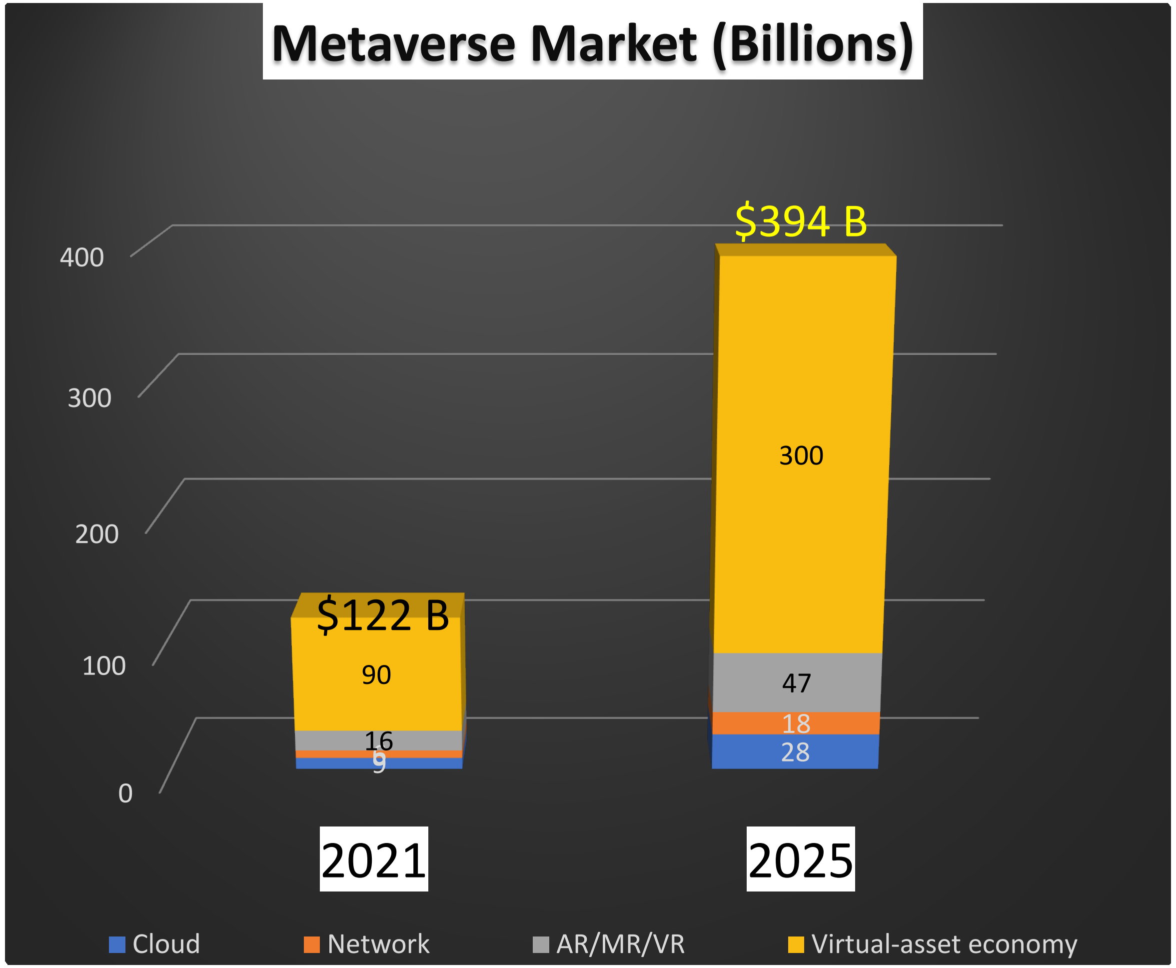
XR/HTC
- Hardware
- Software
- Mobile Ads

Existing PC, Mobile, and Tablet Hardware and Software

Requires Bandwidth & Cloud

Networks and Cloud Infrastructure

Existing Blockchain Network and Cloud Infrastructure



Metaverse Worlds (more than 10K)

- **Decentraland**

  (2015: Argentina; one of the hottest Virtual World; Divided into plots of land and themed neighborhoods that users can explore. Starting price: 13$K; Genesisplaza, Fashion District to Vegas City and District X)

- **Robbox**

  (Platform for many other games; 200 Million games on its platform; Developers make 1M$/year; Free download)

- **Somnium Space**

  (VR setup; infrastructures, games, marketplace, community; Users can build virtual parks, schools, cinemas; can host events, art galleries, music concerts or educational talks)

- **Second Life**

  (2003; 3D Interactive environment (mixing gaming/social networks with real world); many avatars)

- **Cryptovoxels**

  (built on Ethereum; Virtual world for displaying and selling NFT and much more. Virtual galleries help to artists)

- **Sandbox**

  (2012; 3D and Blockchain empowered game; NFT based game; Shifted to Metaverse in 2021; Cryptocurrency called SAND. Create VIRTUAL MEGACITY. Working with many real estate, entertainment, finance gaming, players own land, build and sell properties, monetize their experiences by dealing with NFT tokens)

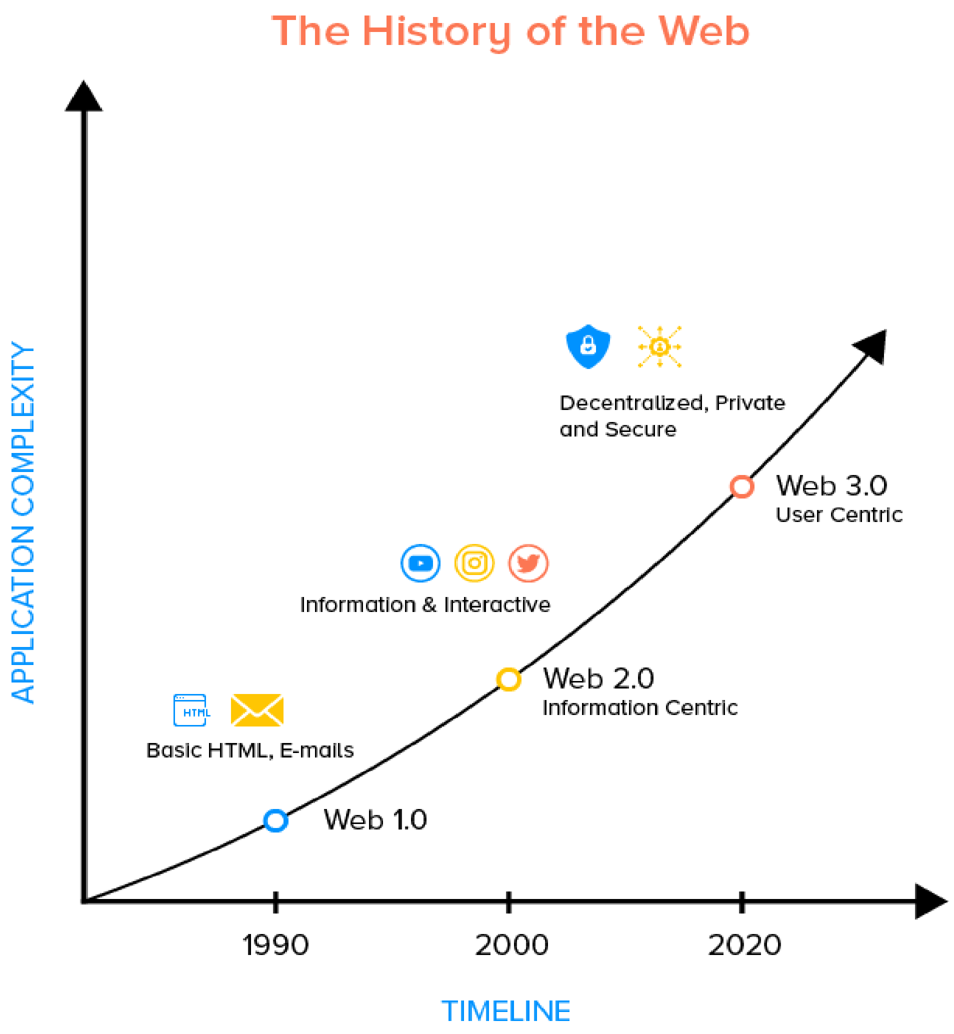
- **WorldWideWebb; Horizon Worlds; Gather; Substrate; Epic Games; NFT Worlds**

Generations of the WWW

- **Web1.0: (1989) (Sir Tim Berners Lee)**
  - **Connect to static website contents and view or download the contents;**
  - **Centralized Infrastructure; Relational Database structures.**

- **Web2.0: (2004) (Tim O'Reilly)**
  - **Dynamic content websites and applications created by users.**
  - **Social Networks. Cloud based Architectures/Centralized.**
  - **Sophisticated web technologies.**

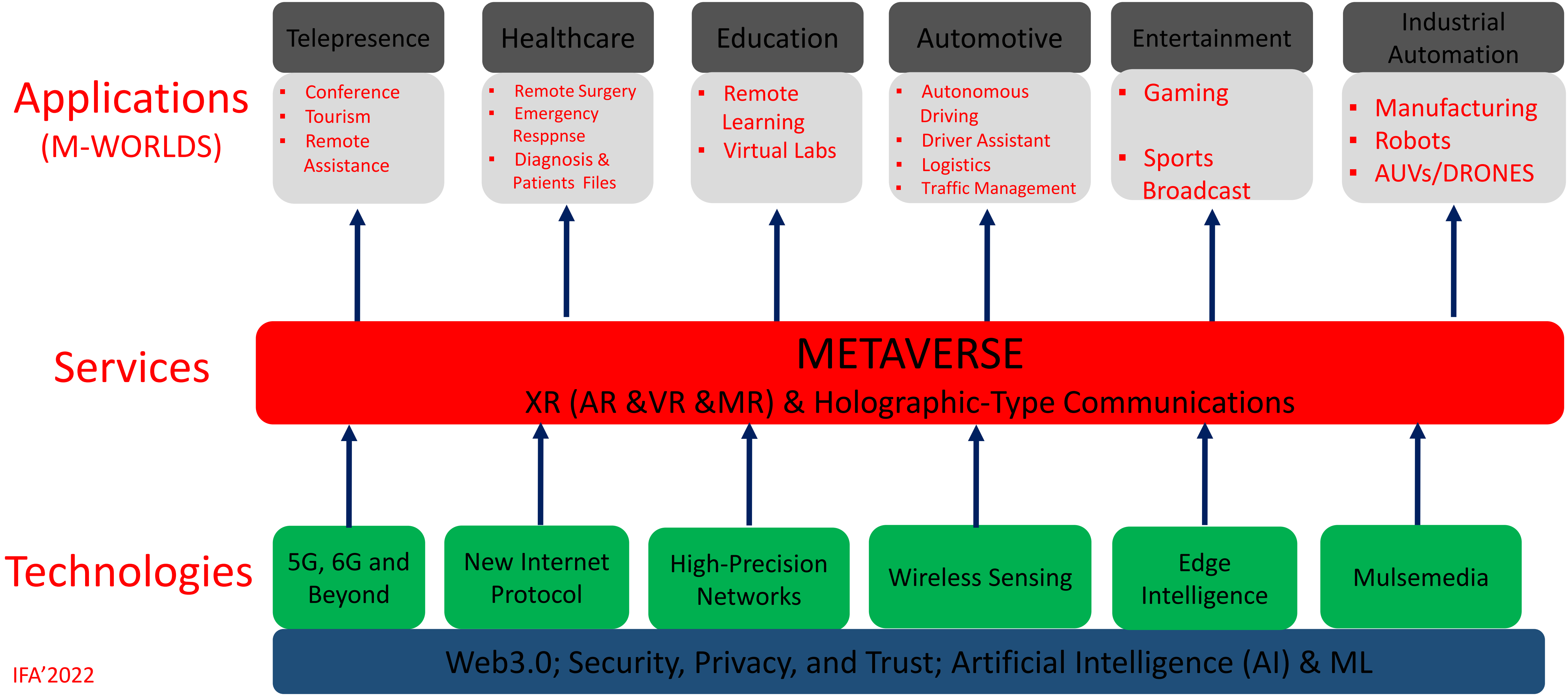
- **Web3.0: (2015) Gavin Wood (Ethereum co-founder)**
  - **Still under development. Metaverse Worlds, Semantic Contents,**
  - **Heavily based on AI/ML based technologies; Decentralized; Edge Computing;**
  - **Peer to Peer; Blockchain based distributed services;**
  - **Focused on digital ownership, such as cyrptocurrency and nonfungible tokens (NFTs).**



Web 3.0: A Decentralized Future

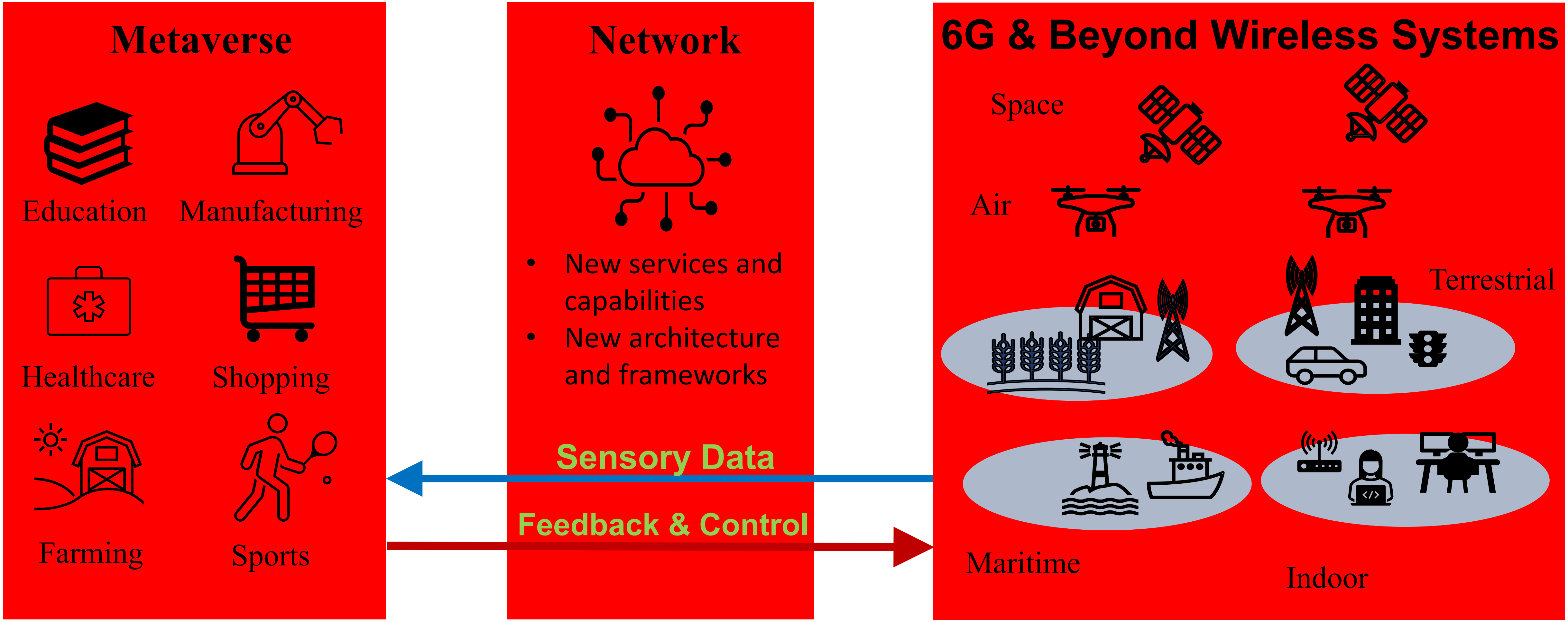
	WEB 2.0 APPS	→	WEB 3.0 DAPPS	
Browser	Chrome	→	Brave	https://brave.com
Storage	Dropbox, Google Drive	→	Storj, IPFS	https://www.storj.io
Social Network	Facebook, Twitter	→	Steemit, Akasha	https://steemit.com
Messaging	Wechat, WhatsApp	→	Status	https://status.im
Cryptocurrency Exchange		→	IDEX, Sapien	https://idex.io
Streaming Services	Netflix, Spotify	→	ySign, UJO music	https://www.ysign.app
Insurance and Banking	The General	→	Casha, Safe Share	https://cashaa.com

NETWORKING 2030-2040



6G and Beyond for the Metaverse

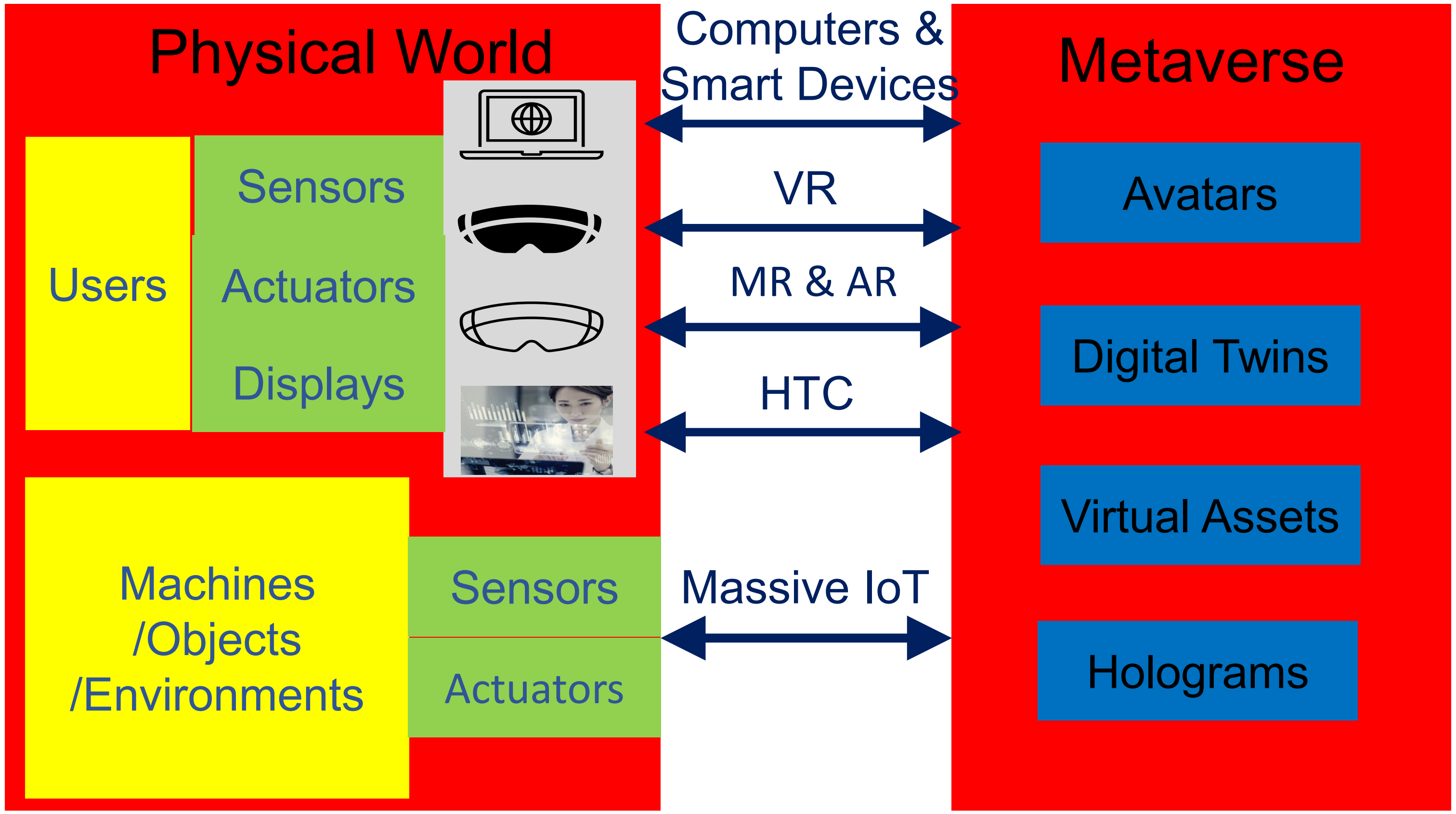
I.F. Akyildiz, H. Guo and R. Dai,
"Entering the Metaverse through 6G Wireless Communication Systems",
Submitted for publication in Oct. 2022.



- **Computer networks and 6G & beyond wireless systems connect the Metaverse with the physical world**

Metaverse Gateways

- **Human and Metaverse Communication:**
  - **High data rates, low latency, high reliability, & ubiquitous connectivity**
  - **Computers, smart devices, VR, MR, AR, & HTC**
- **Machine and Metaverse Communication:**
  - **Massive IoT**
  - **Ubiquitous connectivity**



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(AR/VR/MR)

*** HOLOGRAPHIC-TYPE COMMUNICATION**

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- I.F. Akyildiz and H. Guo, “Wireless Extended Reality (XR): Challenges and New Research Directions”, ITU J-FET journal, April 2022.

. ** I.F. Akyildiz and H. Guo, “Hologram Type Communication: A New Challenge for the Next Decade”, ITU-J-FET journal, September 2022.

XR: EXTENDED REALITY (AR, MR and VR)

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

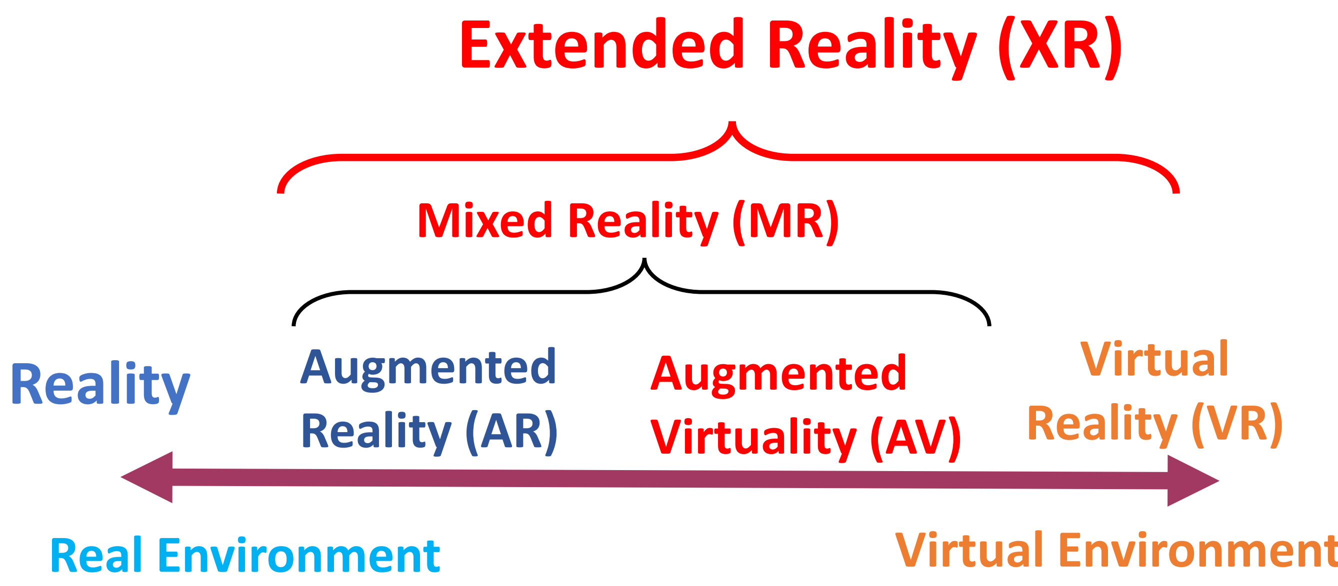
Reality:
Human perception of real objects is based on five basic senses:
Sight, Hearing, Touch, Smell, and Taste

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

XR → Umbrella term for AR and VR

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

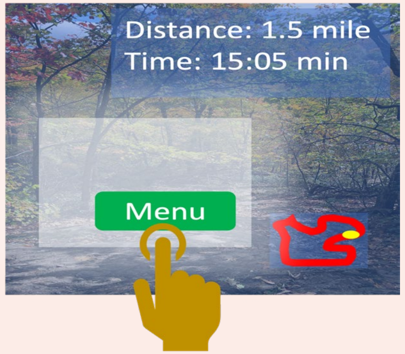
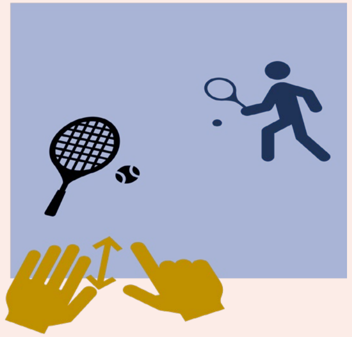
P. Milgram and F. Kishino,
"A Taxonomy of Mixed Reality Visual Displays"
IEICE TRANSACTIONS on Information and Systems, 1994.



Reality-Virtuality Continuum

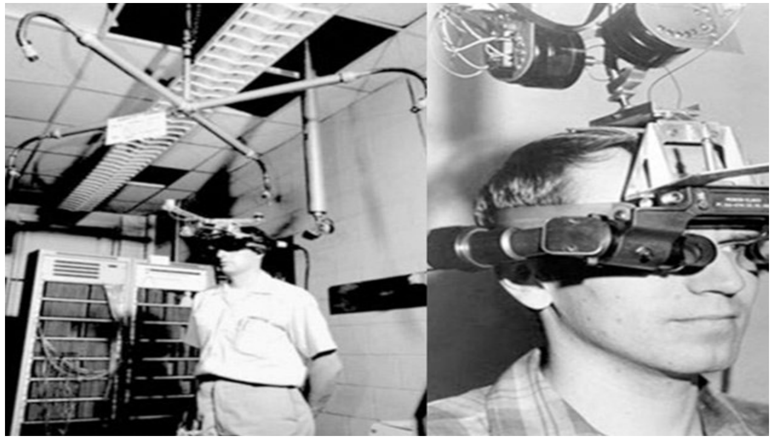
New techs AI/ML, IoT, 5G/6G, make these realities possible !

Devices & Use Cases

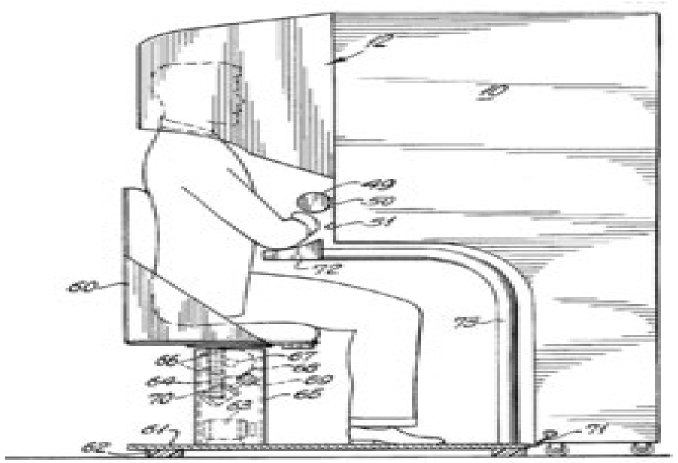
		Extended Reality (XR)		
	Reality	Augmented Reality (AR)	Mixed Reality (MR)	Virtual Reality (VR)
Display	Naked Eye/Optical Glasses	Translucent Display	Translucent Display	Occlusion Display
Display Example				
Example	 Real View of a Trail	 Augmented Virtual Map and Direction	 Interactive Virtual Contents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

Then & Now

Sword of Damocles AR (1968)

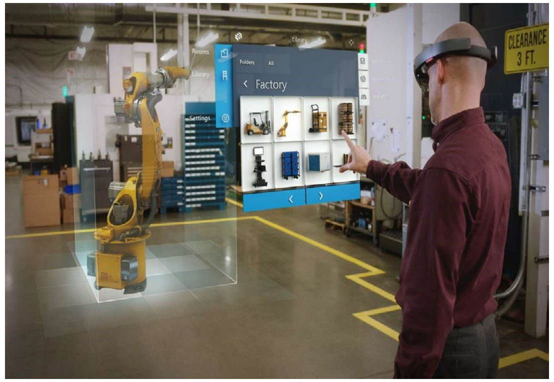


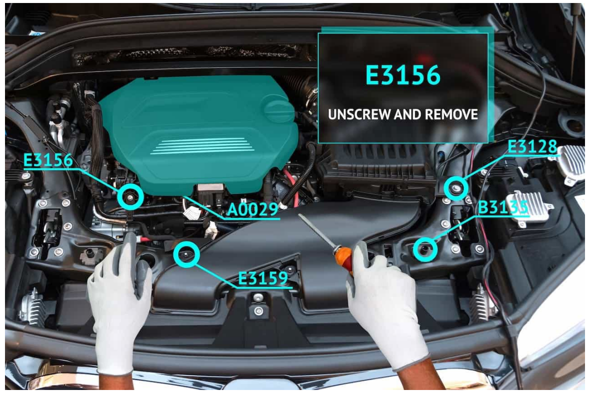
Sensorama VR (1962)



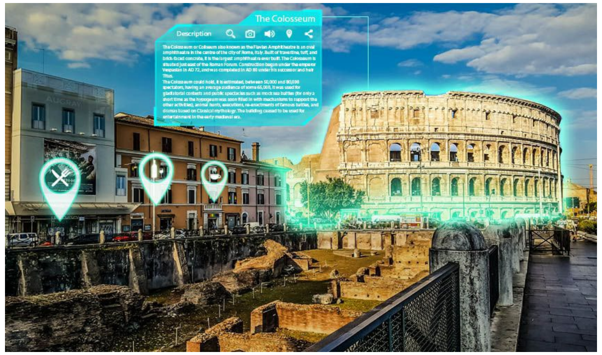
Use Cases

- Entertainment, sports, health care, tourism, education and e-commerce, etc.
- Automotive
- Manufacturing → e.g., training of personnel
- Education
- Gaming
- Remote health care
- Tourism; Real Estate
- Customer can try clothes or beauty products before buying
- How a piece of furniture looks in the living room
- Virtual Home Theater










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	–



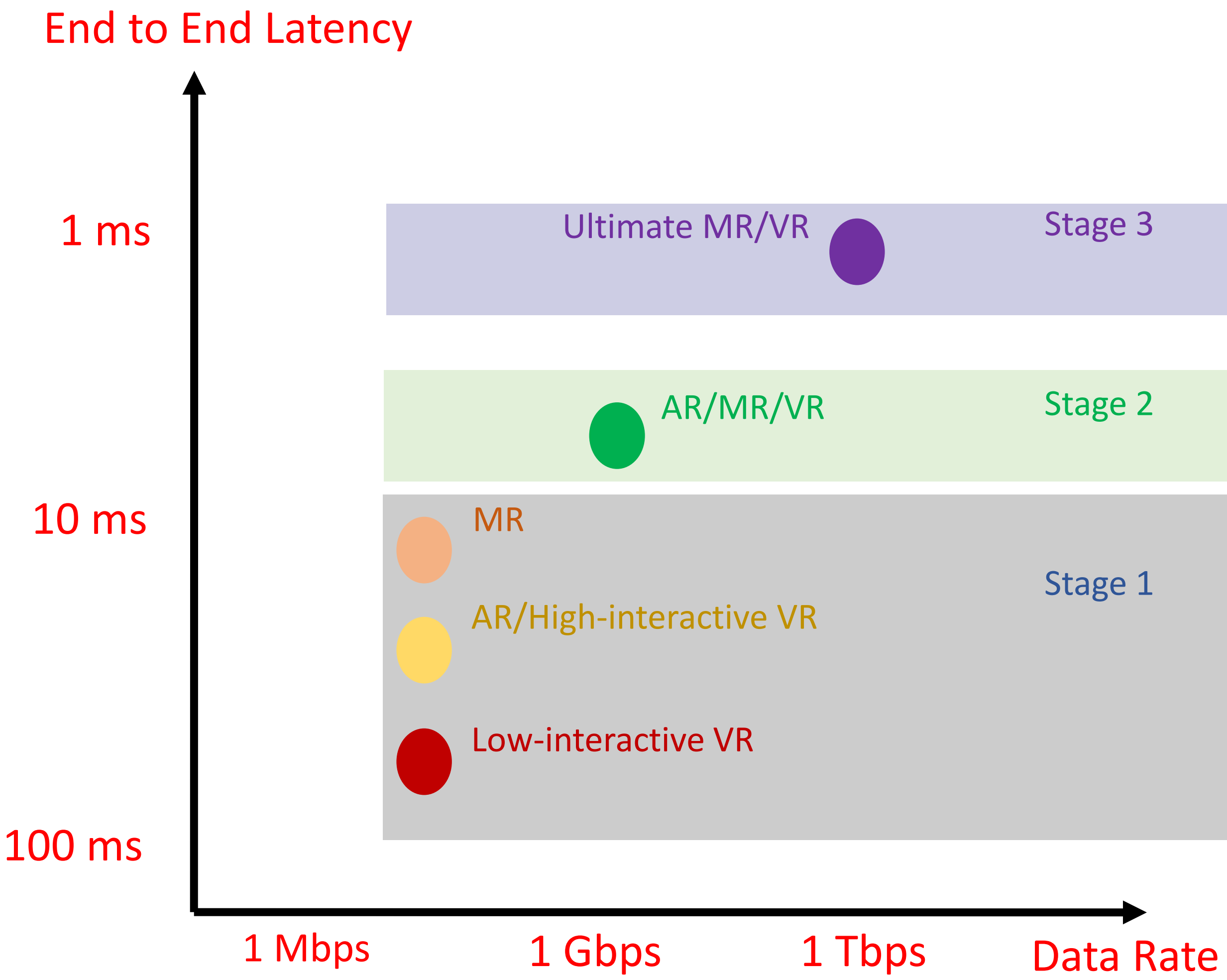



XR Devices: Future

- Tethered heavy headsets
- Low-quality content
- Inconvenient mobility support
- XR sickness for prolonged use

- Untethered wireless headsets
- Lightweight headsets
- High-quality content
- Mobility support

Future: Ultimate XR



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HOLOGRAM

I.F. Akyildiz and H. Guo,
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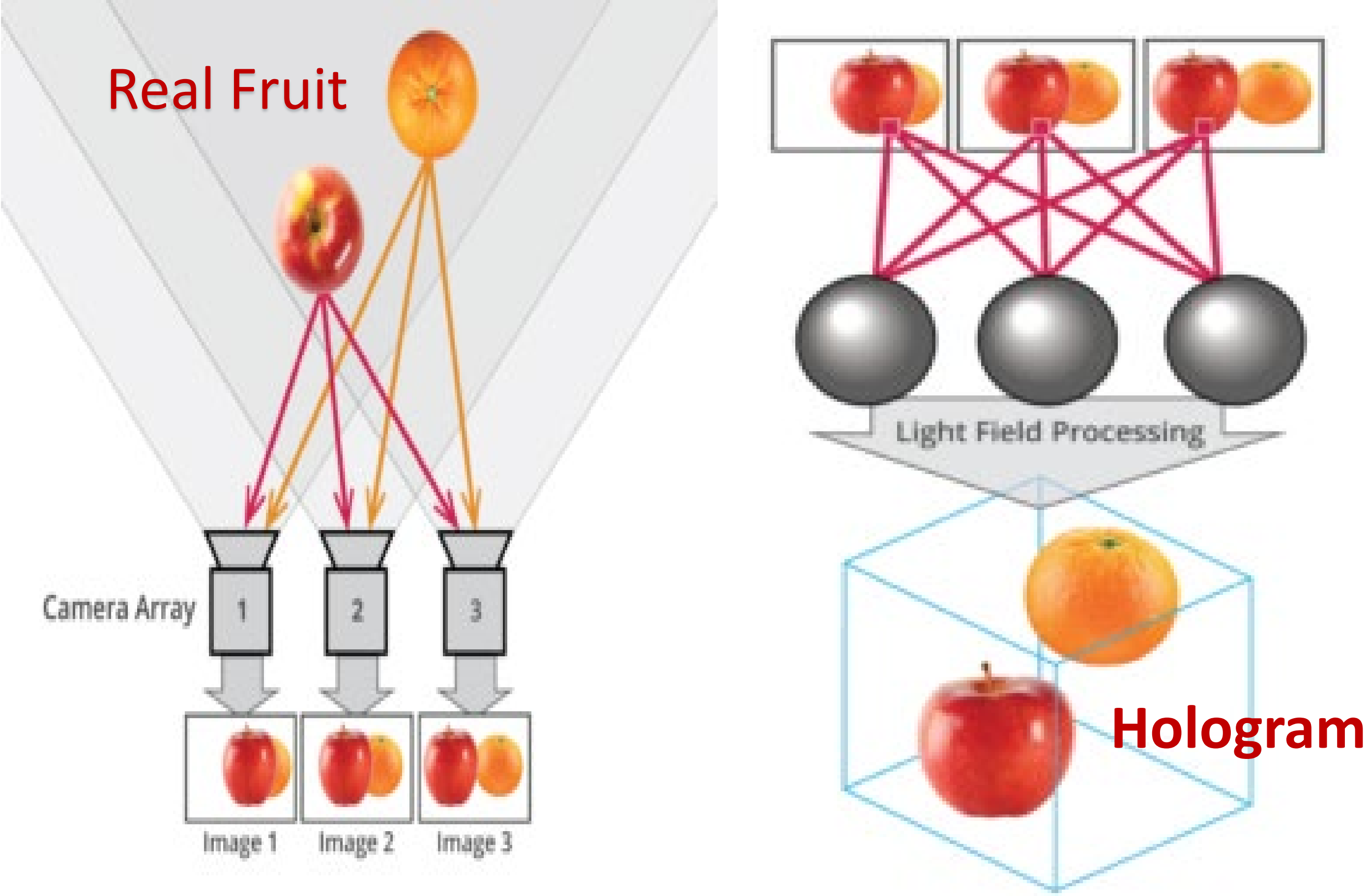
ITU-Journal for Future and Evolving Technologies, September 2022.

- A **Hologram** is a photographic recording of a light field
  - Consists of a set of virtual 3D images that reflect real physical objects, preserving the depth, parallax, and other properties of the original item

- **Holography** is a photographic technique that records the light scattered from an object, and then presents it in a way that appears 3D

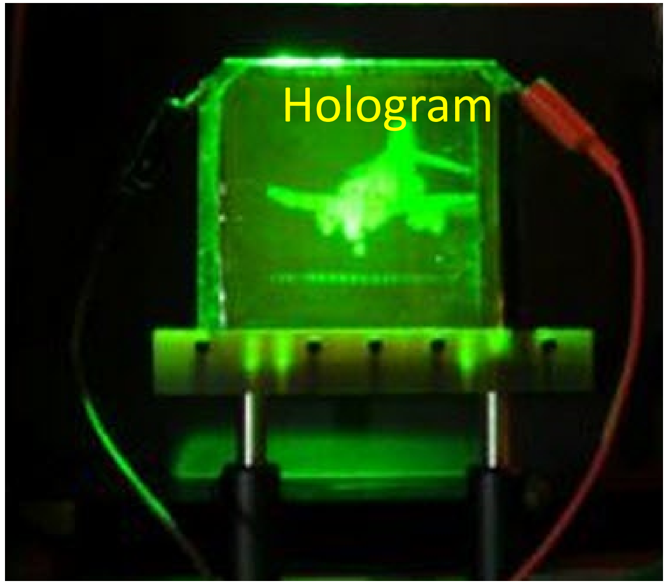


Source: lightfield-forum.com/what-is-the-lightfield/

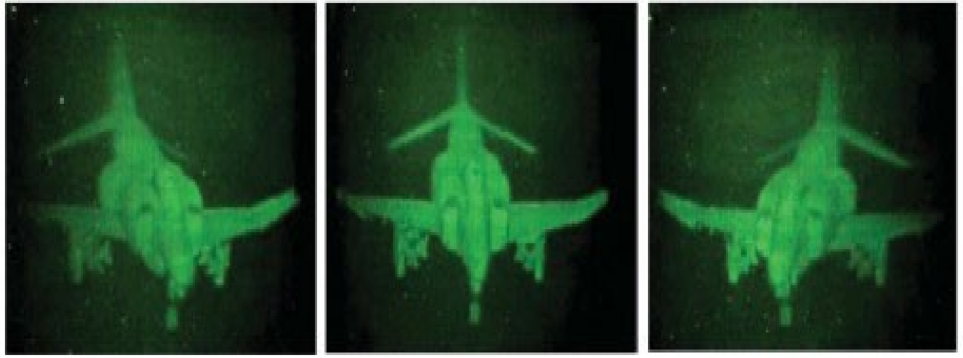
Differences between Hologram and 3D Content

- 3D image is formed by two 2D static views of the same scene (left and right eyes)
- The image is the same regardless of the viewer's position
- Hologram adds parallax, i.e., the viewer can interact with the image → 'User Interactivity Challenge"

Source: Wonderful Engineering



Source: www.kurzweilai.net



Different view angles observe different 3D images

HTC and 5 Senses

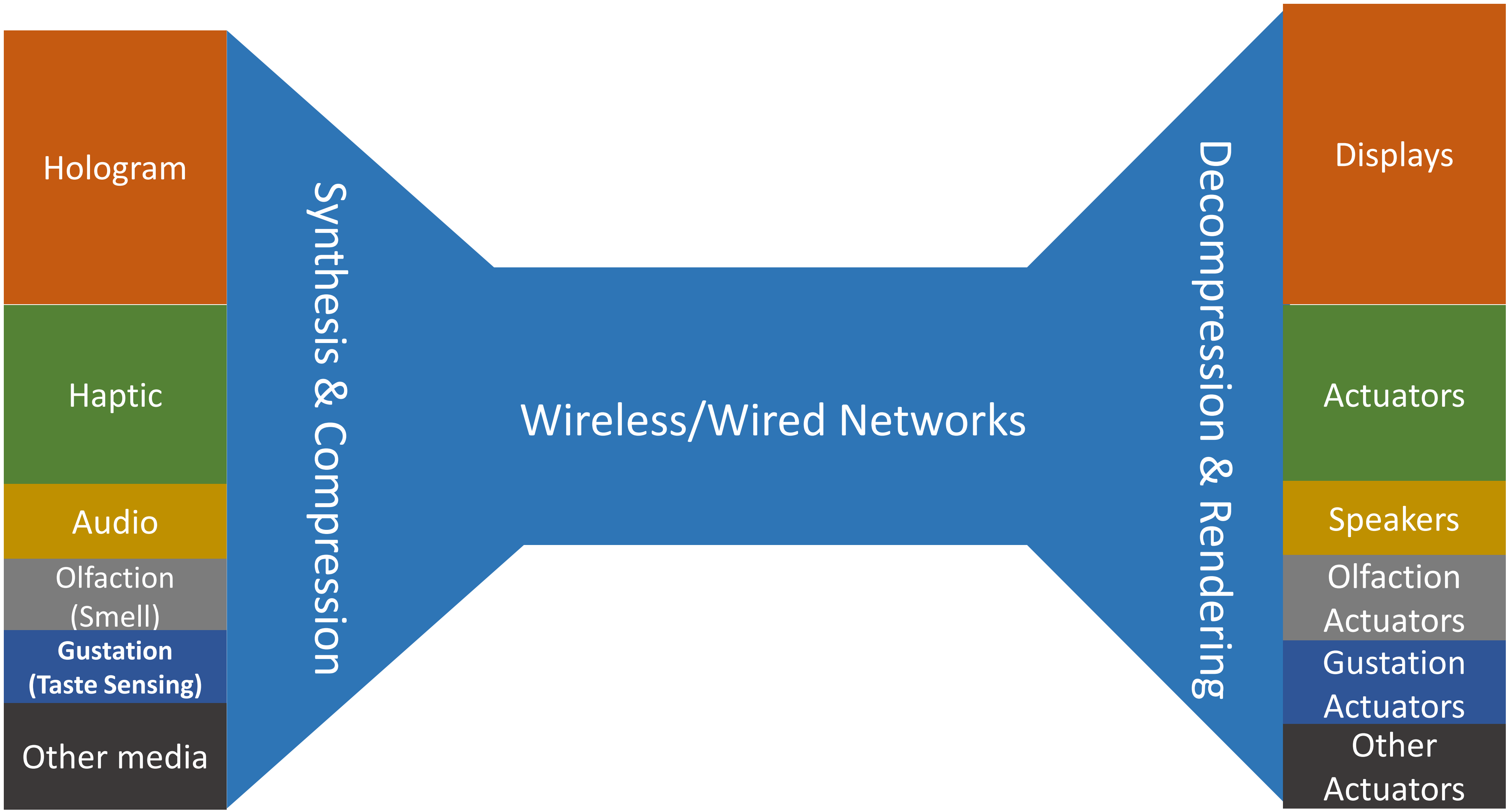
- **HTC is not only about hologram**
- **HTC operates in a true 3D space, and leverages all 5 senses:**

  sight, hearing, touch, smell and taste

- **Mulsemedia (Multi-Sensory Media)**
- **Truly immersive experiences**

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

Mulsemedia Communication



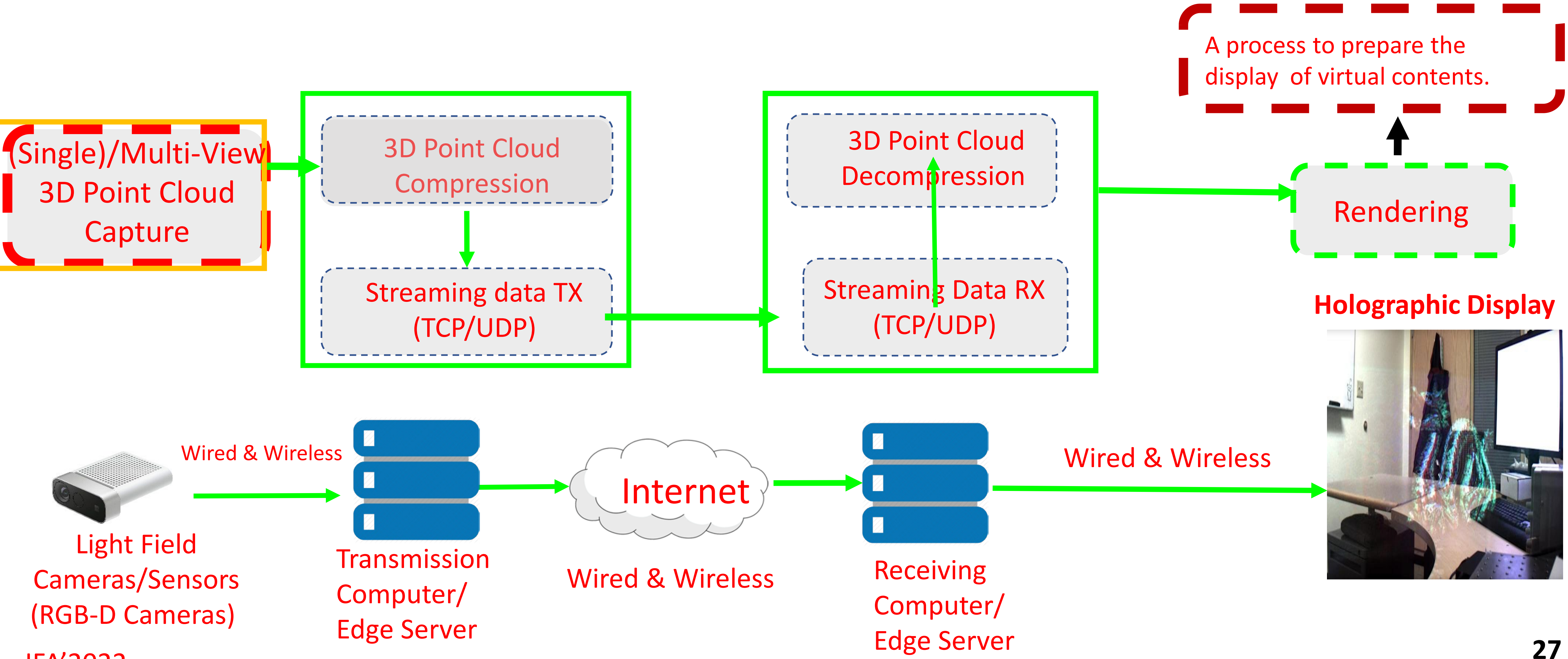
Use Cases

- Earliest: "Telehuman" in 2012
- Near-real person video conferencing
- High resolution remote sensing in challenged areas
- Live sports broadcast using holograms
- Holograms in Education; Conferences etc.

Source: bigthink.com

Source: eu-startups.com

Generic Holographic-Type Communication (HTC) Architecture



1. Source: Representation & Encoding

A. Clemm, M. T. Vega, H. K. Ravuri, T. Wauters, and F. D. Turck
“Toward truly immersive holographic-type communication: Challenges and solutions,”
IEEE Commun. Mag., vol. 58, no. 1, pp. 93–99, Jan. 2020
X. Zhang, et. al.
"Surface Light Field Compression using a Point Cloud Codec”
IEEE Journal on Emerging and Selected Topics in Circuits and Systems 9.1, 163-176, 2018.

Computer-generated Holograms are in 2 types:

- **Image-based Holograms**
  - Use an array of images from different view angles
  - Large-volume of data (>>Tbps)

- **Volumetric-based Holograms → Current Trend**
  - An array of images and depth information are used to create point cloud
  - The actual object is adaptively rendered for any view angle

Light Field Cameras
Source: Road to VR

Multiview Images

Point Cloud Compression: Bandwidth Requirement > 500 Mbps

Direct Transmit: Bandwidth Requirement > 1Tbps

Tradeoff:

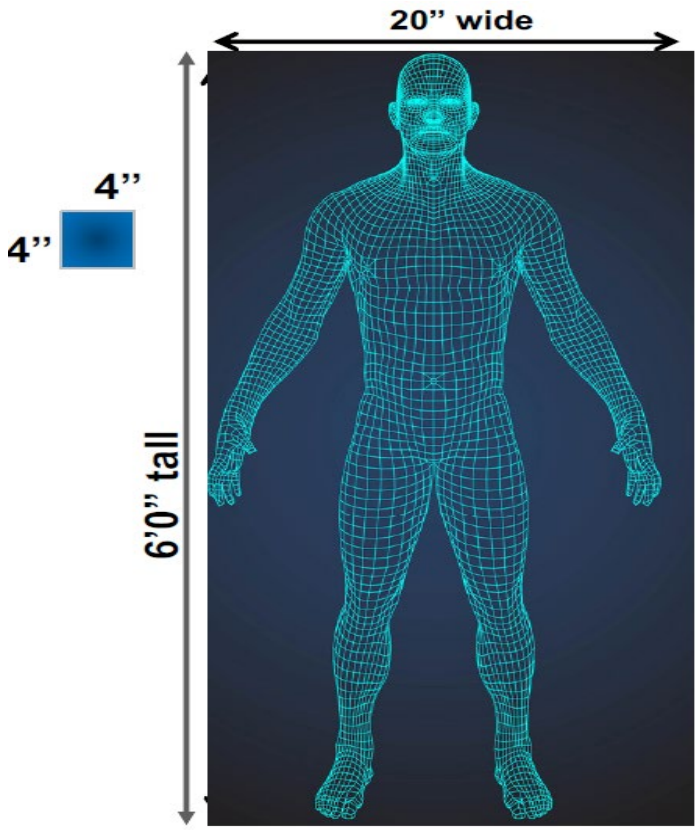
- **Compression (Computation & Latency) and Bandwidth**

1. Source Data Rates

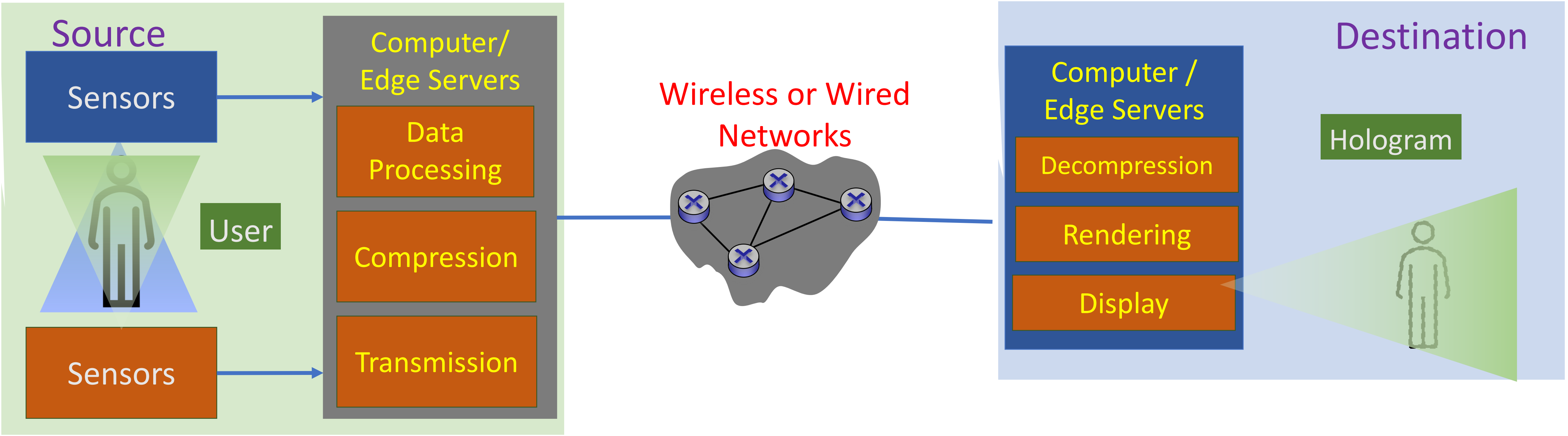
- X. Xu, e. al.
  "3D Holographic Display and Its Data Transmission Requirement."
  IEEE Int. Conf. on Information Photonics and Optical Communications, 2011.
- R. Li
  "Enabling Holographic Media for Future Applications: Identifying the Missing Pieces and Limitations in Networks"
  ACM SIGCOMM 2019 Workshop on Networking for Emerging Applications and Technologies (NEAT 2019) Panel.

- As high as several Tbps
  (raw data without compression)

	Dimension (inches)	Bandwidth (Gbps)
Tile	4x4	30
Human	72x20	4320



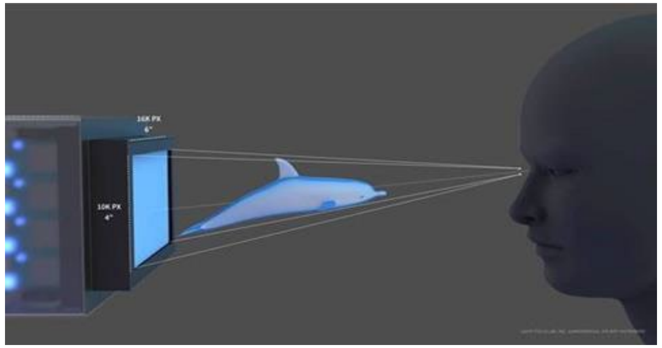
2. Holographic Networks



3. Destination: Holographic Display

Naked Eyes

Light Field Display
> 1000 Views



Source: fxguide.com

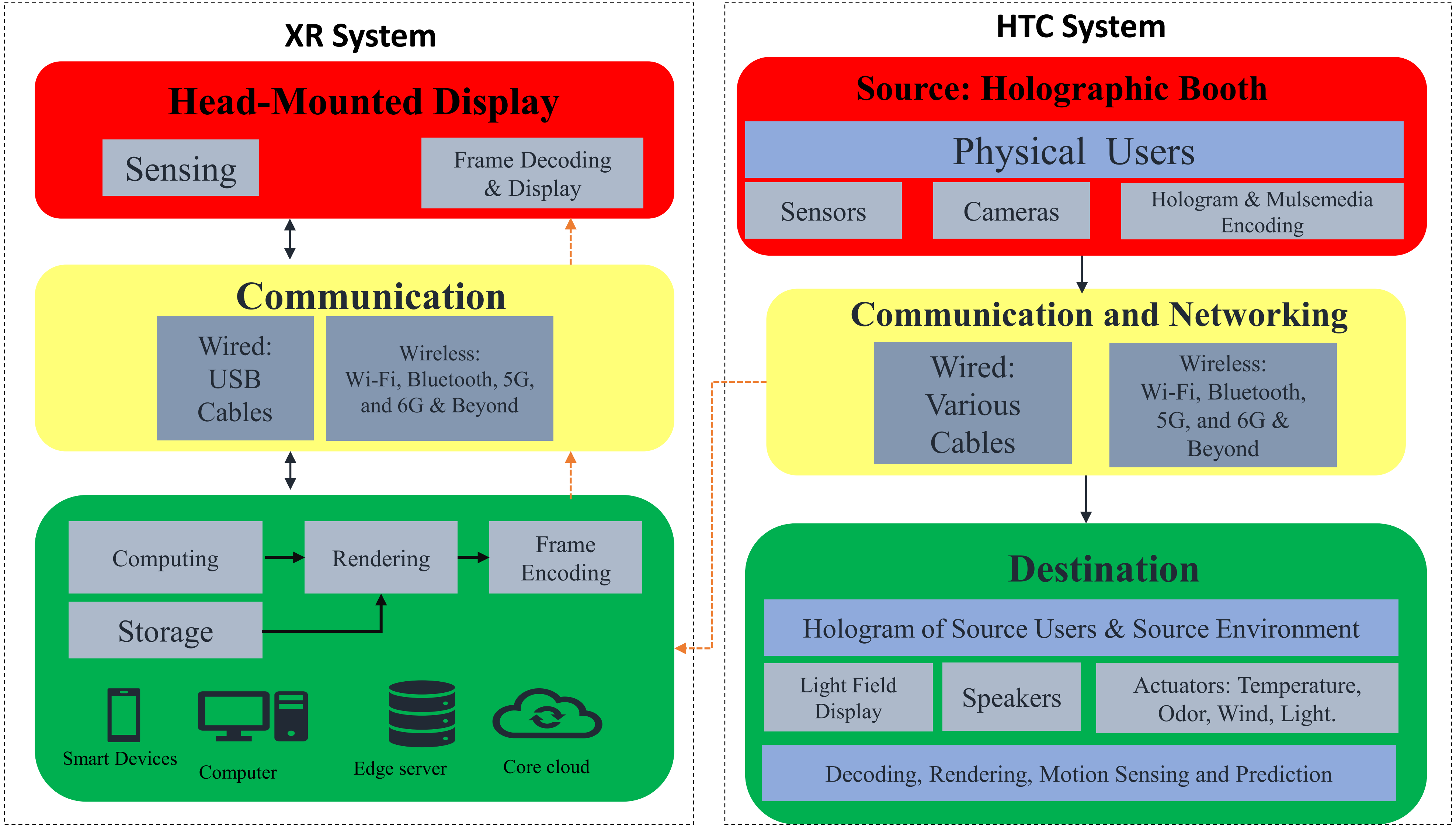
Volumetric Display
> 20 Views

Source: TechEBlog

Extended Reality
Head-Mounted Displays
> 2 Views

2D Display (Cannot display hologram)
1 View

XR and HTC Communication Architecture



XR vs HTC

	eXtended Reality (XR)	Holographic-Type Communication (HTC)
Senses	Sight, Hear, Touch	Sight, Hear, Touch, Smell, Taste
Displays	Head-Mounted Displays	• Head-Mounted Displays • Multi-View Volumetric Displays (observe with naked eyes) • Light Field Displays (observe with naked eyes)
Data rates	1 Gbps	1 Tbps
Latency	< 20 ms	< 1 ms
Synchronization	$\geq$ 2 views and multimedia	> 1000 views and mulsemedia

Metaverse Requirements

	Video	VR	MR & AR	Holographic-Type Communication
Data Rates	35～100Mbps	35Mbps～15Gbps	35Mbps～15Gbps	1～10 Tbps
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

- **Metaverse applications will place significant demands on networking, computing and communication technologies → NOT supported today !**

Metaverse Research Directions from Communications, Networking and Computing Perspectives

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

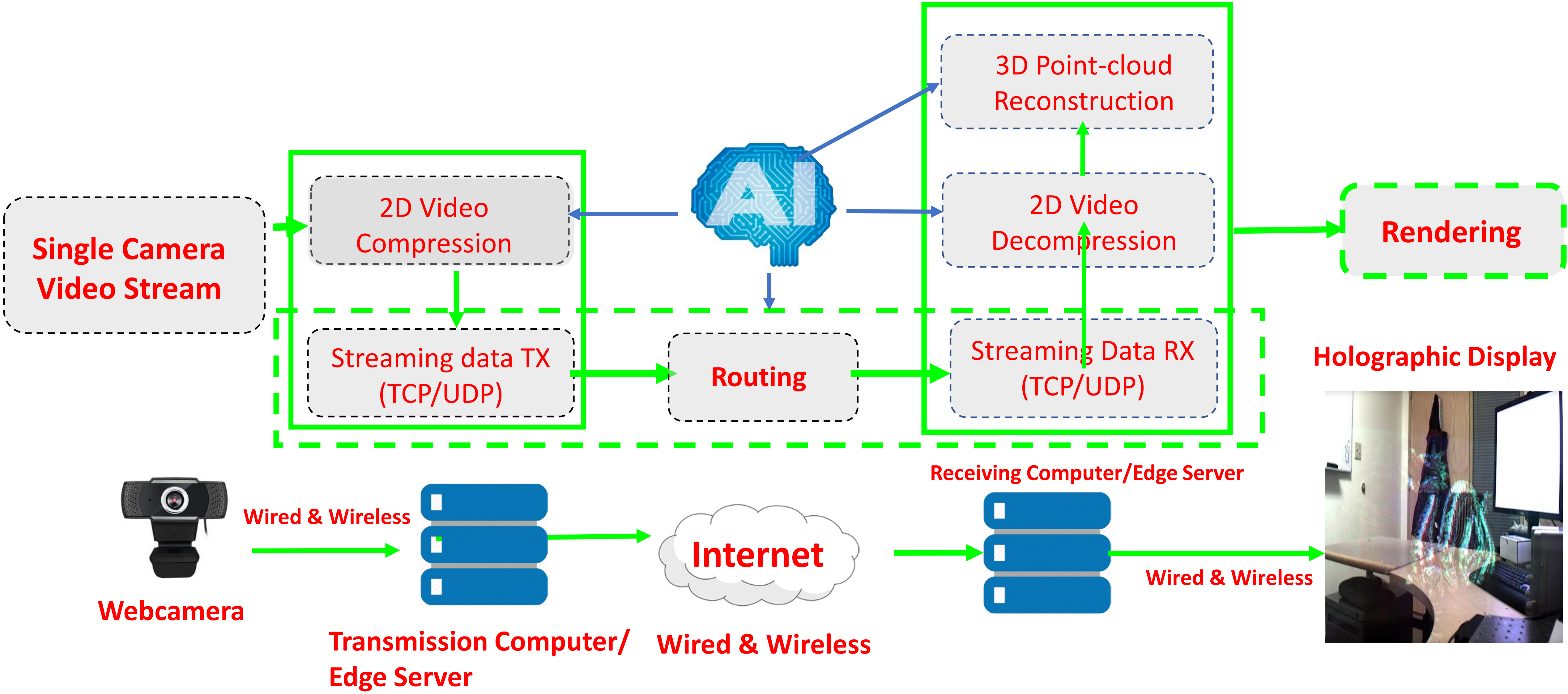
Metaverse Server and User Devices

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

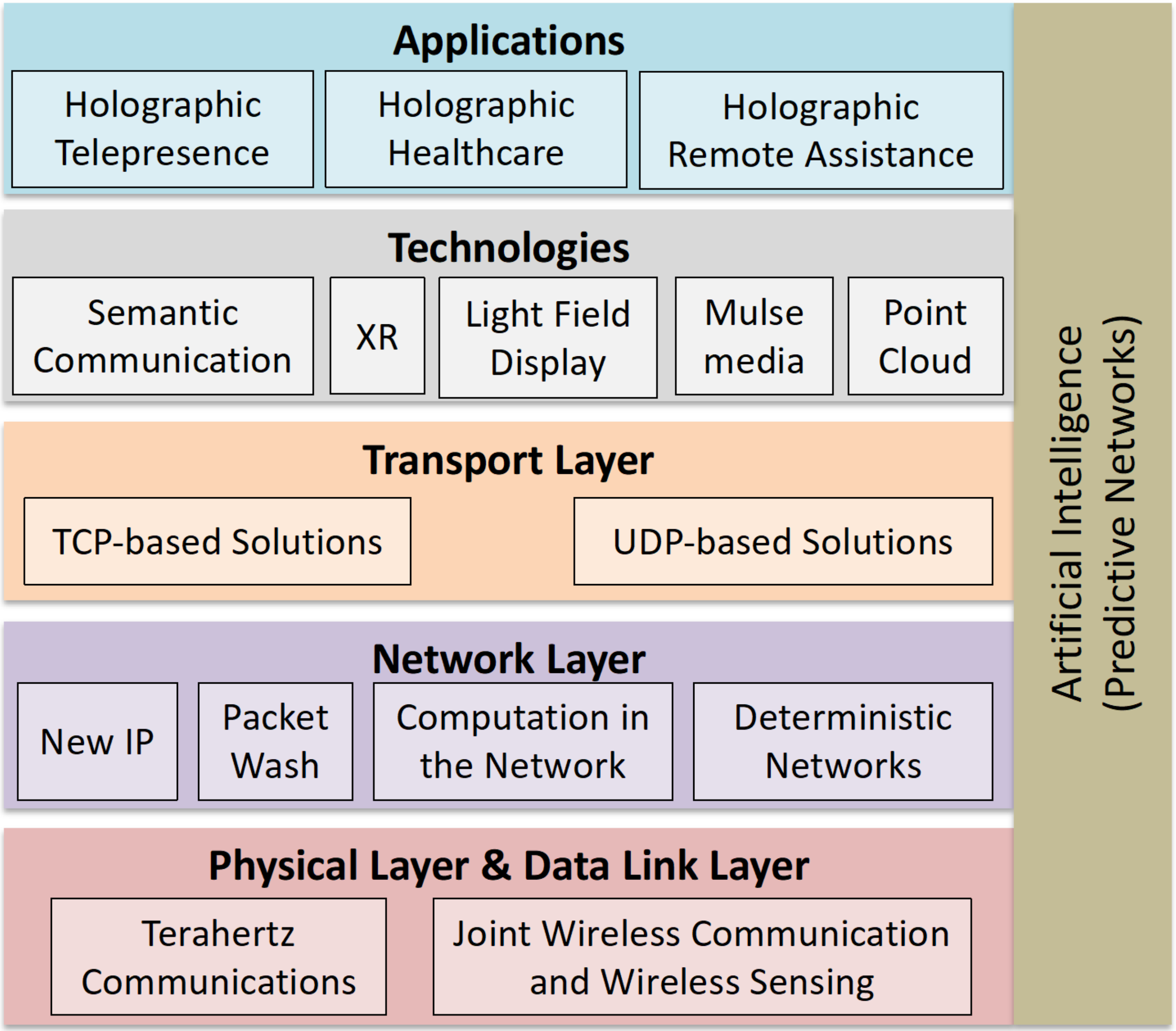
Edge Computing

- 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 Data Compression and Decompression
- High Processing Power: Real time processing

Communication Architecture



Metaverse Potential Protocol Stack



Research Objectives

Transport Layer
- TCP: MPEG DASH
- UDP: QUIC

Network Layer
- New IP Design
- Packet Wash
- Deterministic Networks
- Predictive Networks

Physical & Data Link Layer
- Terahertz Communications
- Joint Wireless Communications and Wireless Sensing

Technologies
- Edge Intelligence
- Semantic Communications
- Point Cloud Encoding & Decoding
- Mulsemedia

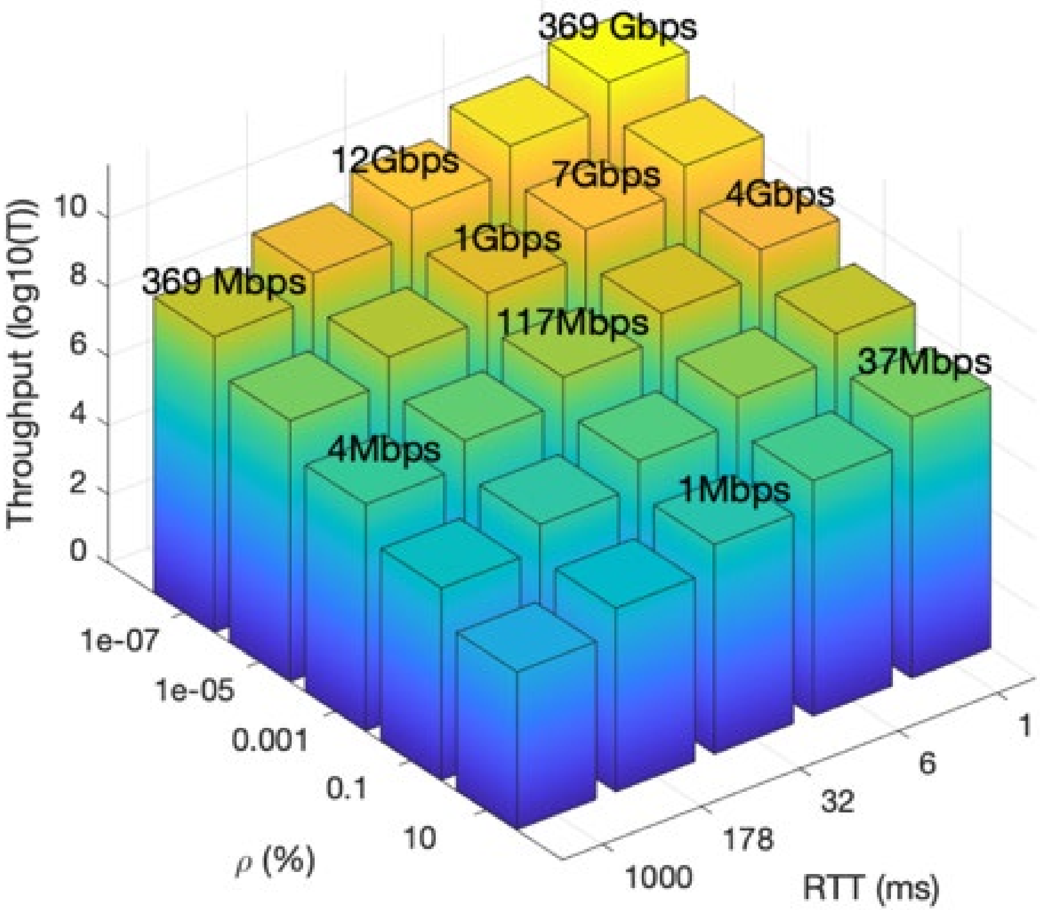
Further Challenges
- Power Consumption & Weight Reduction
- Mobility Effects
- Collaboration in Metaverse

Data Rates: Today's Internet Performance

- TCP Throughput (Cerf-Kahn-Mathis Equation)

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

- 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

Networking Streaming Protocols

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

  - HTTP/TCP-based design
    - Dynamic Adaptive Streaming over HTTP (DASH): a popular solution for streaming stored videos
    - 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 design
    - In favor of lower latency over reliability
    - Need to address loss recovery
    - Real Time Protocol (RTP) for 2D Video mainly
    - Web Real-Time Communication (WebRTC)
    - Quick UDP Internet Connections (QUIC): a promising solution which can prioritize data packets

→ In need of loss-resilient solutions such as error-resilient encoding, error control, recovery, and concealment strategies

Retransmission Problems

- 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

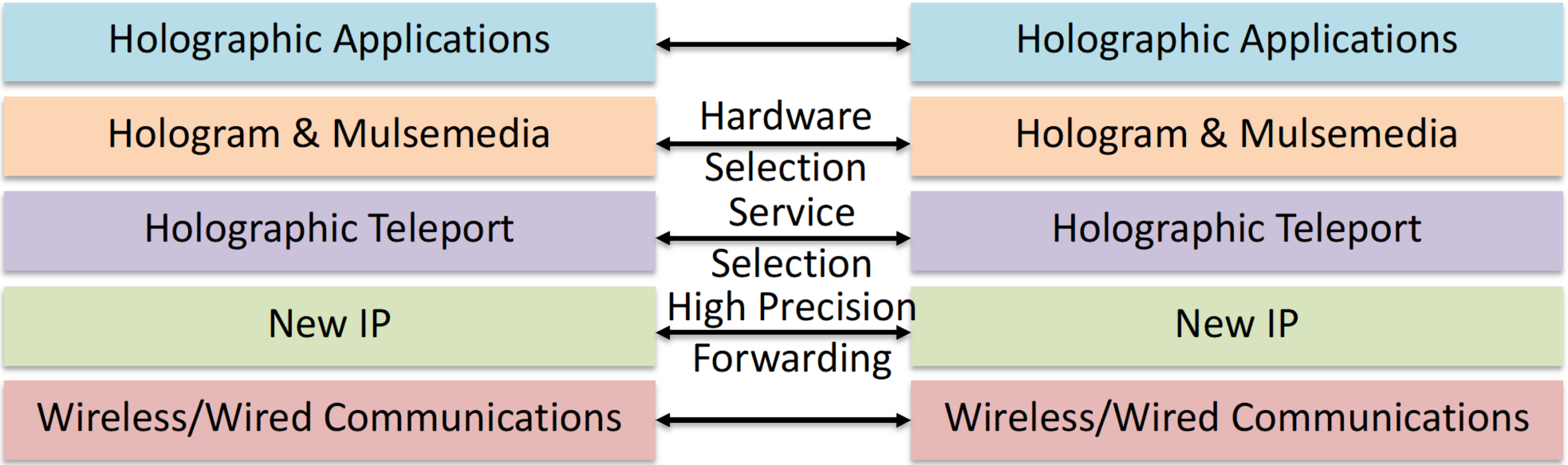
- Avoid retransmission → what causes packets loss and error?
  - Congestion → Drop all the packets
  - Transmission error → Correction or Retransmission

- Potential Solutions:
  - (Networking) **Drop part of the packets → Semantic** Com **and Packet** Wash
  - (User End) **Error Detection &** Correction **using** ML **algorithms**

Research Objectives

Transport Layer	Network Layer	Physical & Data Link Layer	Technologies	Further Challenges
• TCP: MPEG DASH • UDP: QUIC	• New IP Design • Packet Wash • Deterministic Networks • Predictive Networks	• Terahertz Communications • Joint Wireless Communications and Wireless Sensing	• Edge Intelligence • Semantic Communications • Point Cloud Encoding & Decoding • Mulsemedia	• Power Consumption & Weight Reduction • Mobility Effects • Collaboration in Metaverse

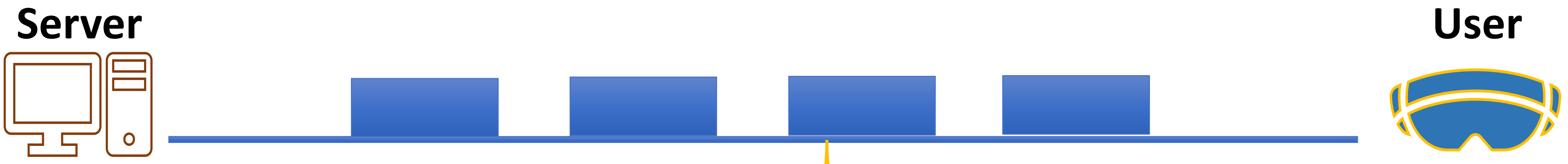
New Internet Protocol



- **New IP: A new network protocol to design network architecture, framework and infrastructure with:**
  - **High-Precision Latency Control**
  - **New Transport Layer Solutions**
  - **Semantic (Quality) Communications**
  - **Free-Choice Addressing: Not only IPv4 or IPv6**

Packet Wash

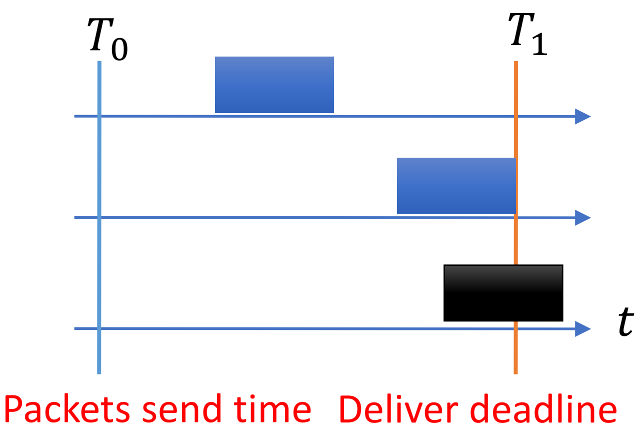
L. Dong, and A. Clemm.
"High-Precision End-to-End Latency Guarantees Using Packet Wash."
Proc. of the IFIP/IEEE Int. Symposium on Integrated Network Management (IM), 2021.



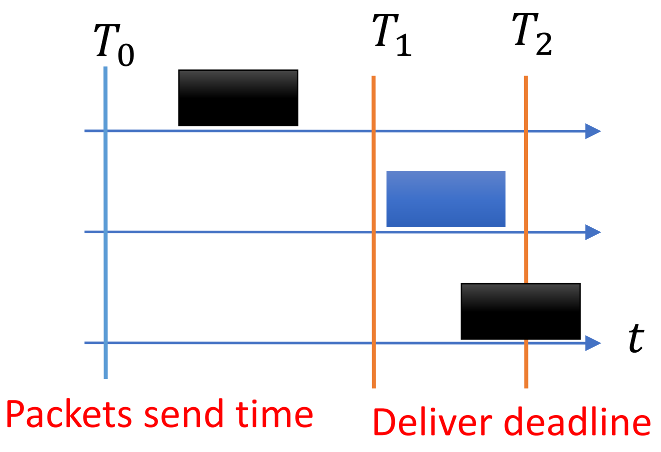
Header	Precision	Mulsemedia	Importance	Action	Payload
	• Latency • Bandwidth • Delivery Time	• Senses Included	• Importance Value	• Drop (Small Importance Value) • Forward (Large Importance Value) • Delay (Precise Latency Control)	

- **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

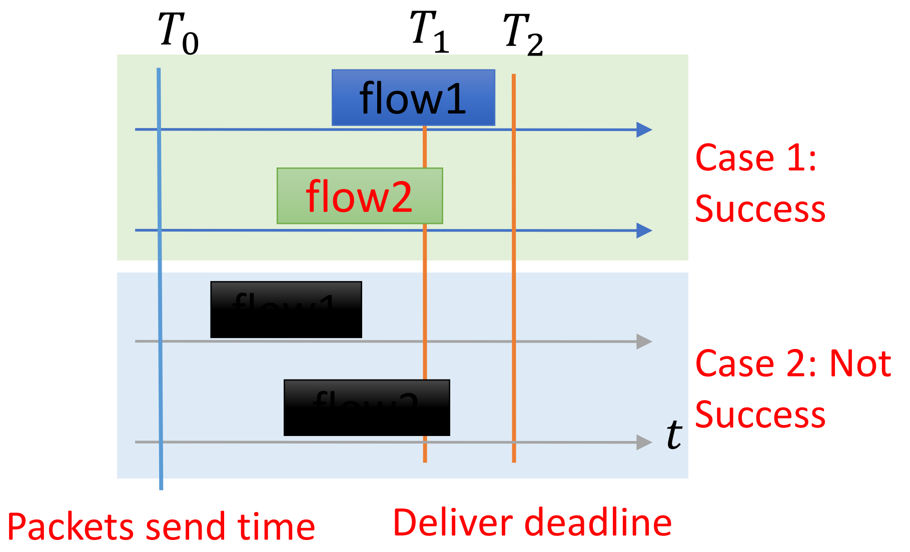
Types of End-to-End Latency Control



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 & Holographic data sizes are 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**

AI-empowered Network Prediction and Adaptive Control

J. P. Vasseur
"Towards a Predictive Internet"
Cisco Report, 2021.

- 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 using AI/ML

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- Mulsemedia

Further Challenges
- Power Consumption & Weight Reduction
- Mobility Effects
- Collaboration in Metaverse

How to deal with PHY and Link Layer Challenges?

- E. Khorov, I. Levitsky, and I. F. Akyildiz.
  "Current status and directions of IEEE 802.11 be, the future Wi-Fi 7." IEEE Access, May 2020.
- I.F. Akyildiz, A. Kak, and S. Nie.
  "6G and beyond: The future of wireless communications systems." IEEE Access, July 2020.
- I. F. Akyildiz, C. Han, Z. Hu, S. Nie, and J. M. Jornet,
  "TeraHertz Band Communication: An Old Problem Revisited and Research Directions for the Next Decade",
  IEEE Transactions on Communications, June 2022.

- 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 future XR and HTC

- Local Area: Next Generation Wi-Fi Systems
  - 802.11 be: around 46 Gbps
  - 802.11 ay: around 100 Gbps

- Wide Area: 5G + 6G & Beyond Wireless Systems
  - 6G peak data rate 1 Tbps and experienced data rate 1 Gbps

How to Deal with PHY and Link Layer Challenges?

- I.F. Akyildiz, A. Kak, and S. Nie.
  "6G and beyond: The future of wireless communications systems." IEEE Access, July 2020.
- I. F. Akyildiz, C. Han, Z. Hu, S. Nie, and J. M. Jornet,
  "TeraHertz Band Communication: An Old Problem Revisited and Research Directions for the Next Decade",
  IEEE Transactions on Communications, June 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
  - 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

Why TeraHertz?

- I.F. Akyildiz, J.M. Jornet, and C. Han,
  "TeraNets: Ultra-broadband Communication Networks in the Terahertz Band,"
  IEEE Wireless Communications Magazine, vol. 21, no. 4, pp. 130-135, August 2014.

- I. F. Akyildiz, C. Han, Z. Hu, S. Nie, and J. M. Jornet,
  "TeraHertz Band Communication: An Old Problem Revisited and Research Directions for the Next Decade",
  IEEE Transactions on Communications, June 2022.

- **6G REQUIREMENTS (Min End to End Latency; Very High Reliability; Very High Data Rates)**

- **Exponential growth of wireless data traffic:**

  - **More Devices → Multi-billion fixed-mobile-connected devices by 2025**

  - **Faster Connections →**

    Wireless data rates have doubled every 18 months over the last three decades

  - **Wireless Terabit-per-second (Tbps) links will become a reality within the next 5 years**

  → HOW??? → Explore high frequencies !!

TERANETS (formerly GRANET; 2008-2013):

"GRAPHENE BASED NANO SCALE communication networks IN THZ BAND"

NSF; US ARMY; FiDiPro; CATALUNA; HUMBOLDT; KACST, etc..

2008-2013; 2013-2016 & 2016-2020 ; 2018-2022

- **Objectives:**
  - To demonstrate the feasibility of graphene-enabled EM communication
  - To establish the theoretical foundations for EM nanonetwork
  - To establish the theoretical and experimental foundations of ultra-broadband com nets in the (0.1-10) THz band

NANO Materials & Devices

- Nano-Transceivers✓
- Nano-Antennas and Arrays ✓
- Fabrication
- Experimental Measurement

THz Channel

- Line-of-Sight ✓
- Multi-path ✓
- 3D End-to-End ✓
- Ultra-massive MIMO
- Noise Modeling ✓
- Capacity Analysis ✓
- Experimental Measurement

THz Communications

- Pulse-based Modulation ✓
- Multi-band Modulation ✓
- Equalization
- Synchronization ✓
- Ultra-Massive MIMO ✓

THz Networks

- Error Control ✓
- Medium Access Control ✓
- Addressing
- Neighbor Discovery
- Relaying
- Routing
- Transport Layer
- Cross-layer

Experimental and Simulation Testbeds

CHALLENGES IN THz Band Communications in Outdoor Scenarios & MOBILE SYSTEMS

GRAND CHALLENGE: DISTANCE PROBLEM !!

Akyildiz, I. F., Han, C., and Nie, S., "Combating the Distance Problem in the Millimeter Wave and Terahertz Frequency Bands," IEEE Communications Magazine, vol. 56, no. 6, pp. 102-108, June 2018.52

- Longer Transmission Distances

  (High Attenuation)

- Shadowing effects caused by dense obstructions such as buildings

- Higher signal energy dispersion caused by frequency-selective fading

- Higher mobility of tx and scatterers in environments which lead to larger Doppler shift

- Scintillation effect (atmospheric turbulence) due temperature & humidity of environment

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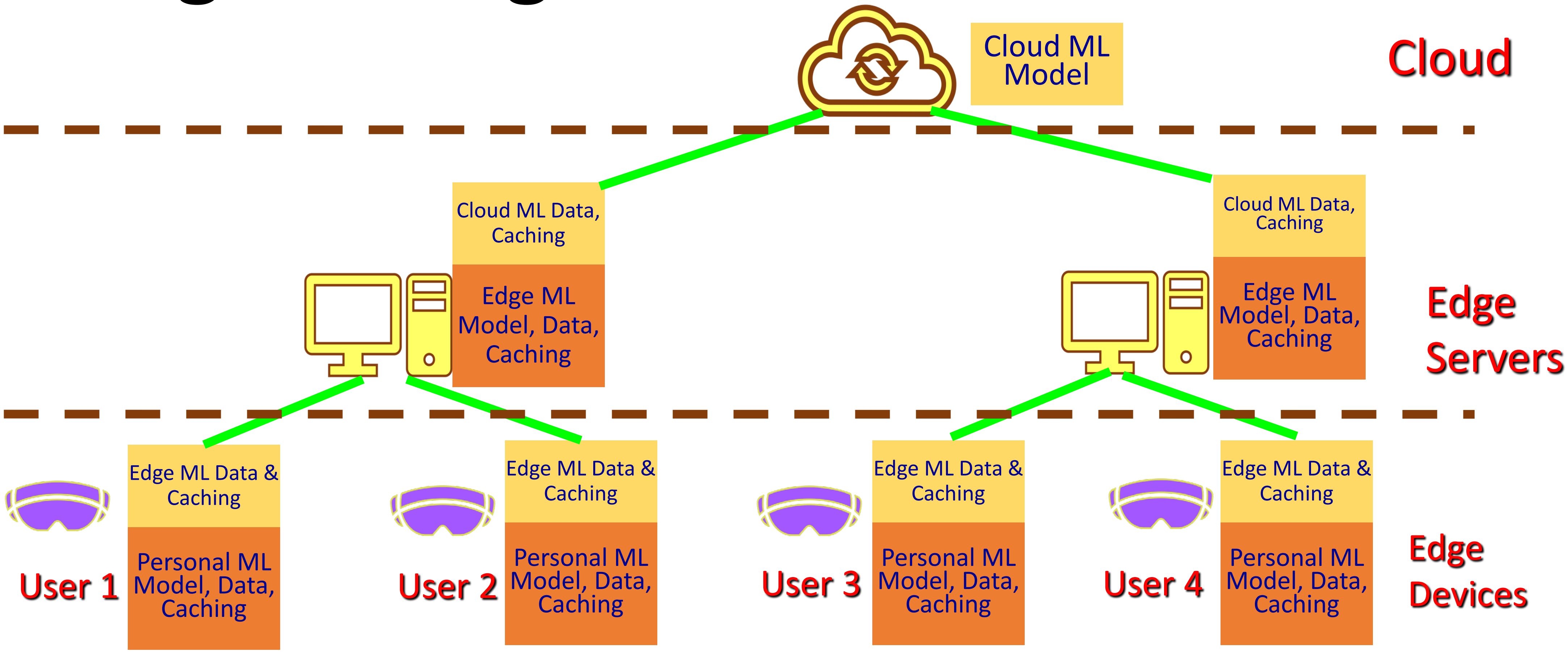
Edge Intelligence



- 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 Metaverse Systems

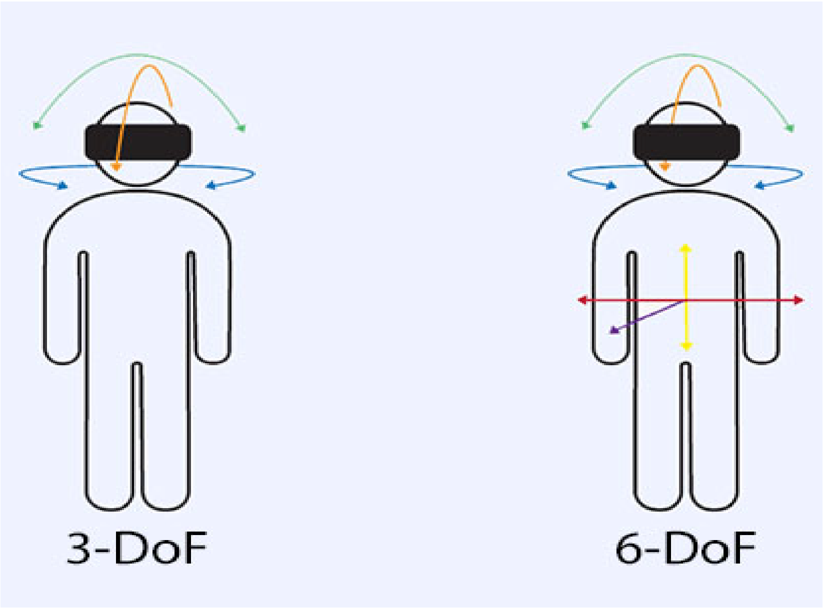
D. Xu, et al.
"Edge Intelligence: Empowering Intelligence to the Edge of Network."
Proc. of the IEEE 109.11, pp. 1778-1837, 2021.

CONTENT GENERATION:

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

USER DEVICES:

- **Edge Devices:** Displays, Sensors & Actuators
- **Intelligence of Error Correction, User Behavior Prediction and QoE Improvement**
- **User Motion Prediction (6-DoF):** 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



Edge Intelligence in Metaverse Systems

NETWORKING:

- **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**

Quantitative Communication vs Semantic (Qualitative) 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

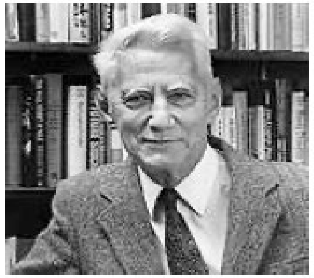
Semantic Communications

Recent Contributions to
The Mathematical Theory of Communication

Warren Weaver

September, 1949

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



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 CHALLENGES

- Lack of a fundamental theory --> semantic entropy, semantic channel capacity, etc.
- What is a metric for quality communication (in terms of semantic communication)?
- How do you distinguish/define the subjective perception differences at the receiver side?
- How do we decide/determine the quality of data? Quality of data may be different for each person or machine?
- How do we construct and update the massive knowledge base?
- How do we carry out cross layer model and joint optimization???

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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

BONUS CHALLENGES

- DEVELOPMENT OF EFFICIENT HOLOGRAM ENCODING AND DECODING TECHNIQUES
- QoE-aware design and AI/ML-empowered wireless sensing and motion prediction at the source and destination
- Precise Synchronization of Mulsemedia (Multiple Senses)
- Design HTC mulsemedia sensors and actuators.
- Study mulsemedia end-to-end latency requirements.
- How to optimally perform sensing for light field display users?
- How to predict users' motion based on collected sensing data?
- How to mitigate the impact of prediction errors?
- AI/ML EMPOWERED ERROR DETECTION/CORRECTION AND NETWORK PREDICTION, ADAPTIVE CONTROL, MANAGEMENT

Conclusion

- **Metaverse is not only an emerging technology, but also a platform for economy, entertainment, and many other applications**

- **Web3.0, Extended Reality (XR), and Holographic-Type Communications (HTC) are enablers for Metaverse**

- **Communication & networking is a bottleneck to realize the Metaverse**

- **6G and Beyond will enable Metaverse using semantic communications, precise network control, AI, ML, SDN, NFV, Automatic Network Slicing, New IP, New lightweight protocols, etc.**