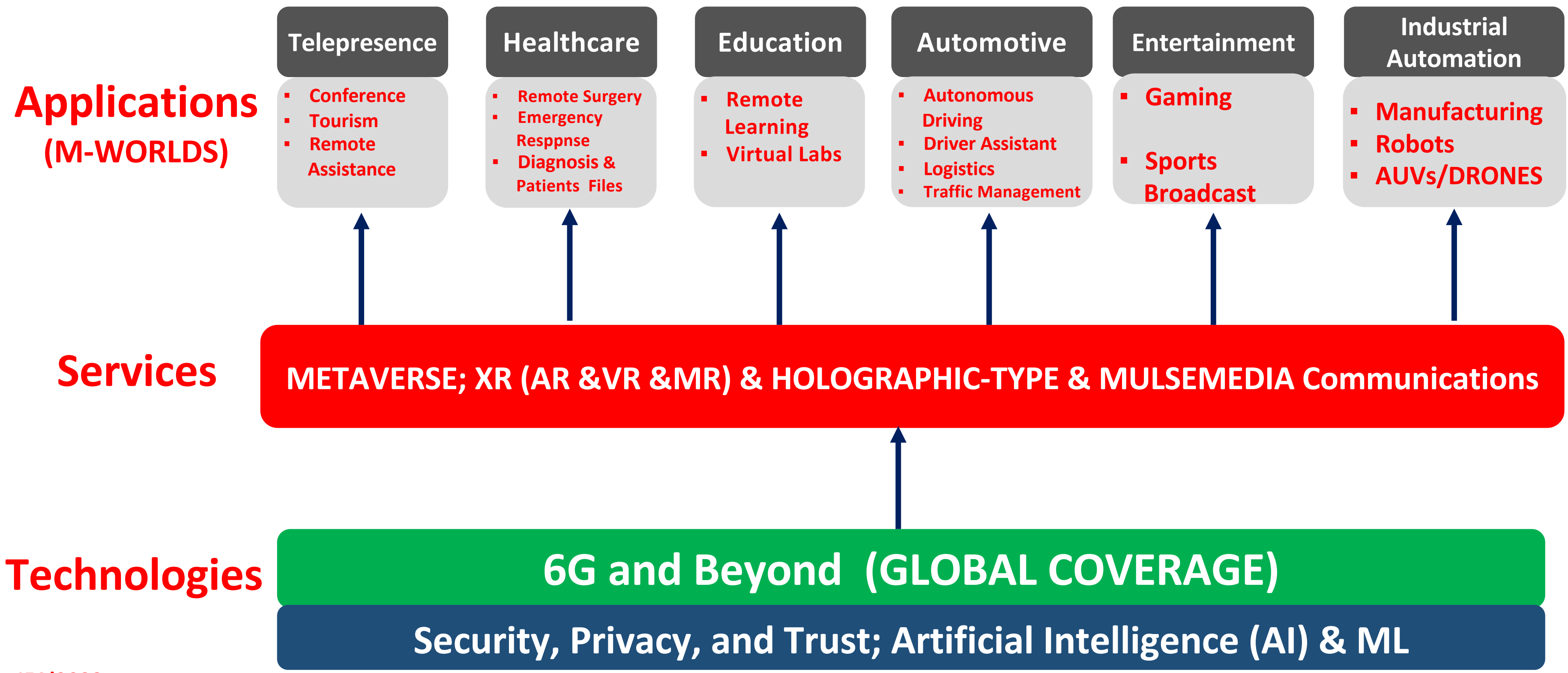
NETWORKING 2030:
METAVERSE, EXTENDED REALITY, HOLOGRAM TYPE and MULSEMEDIA COMMUNICATION CHALLENGES IN 6G and BEYOND SYSTEMS

I.F. AKYILDIZ

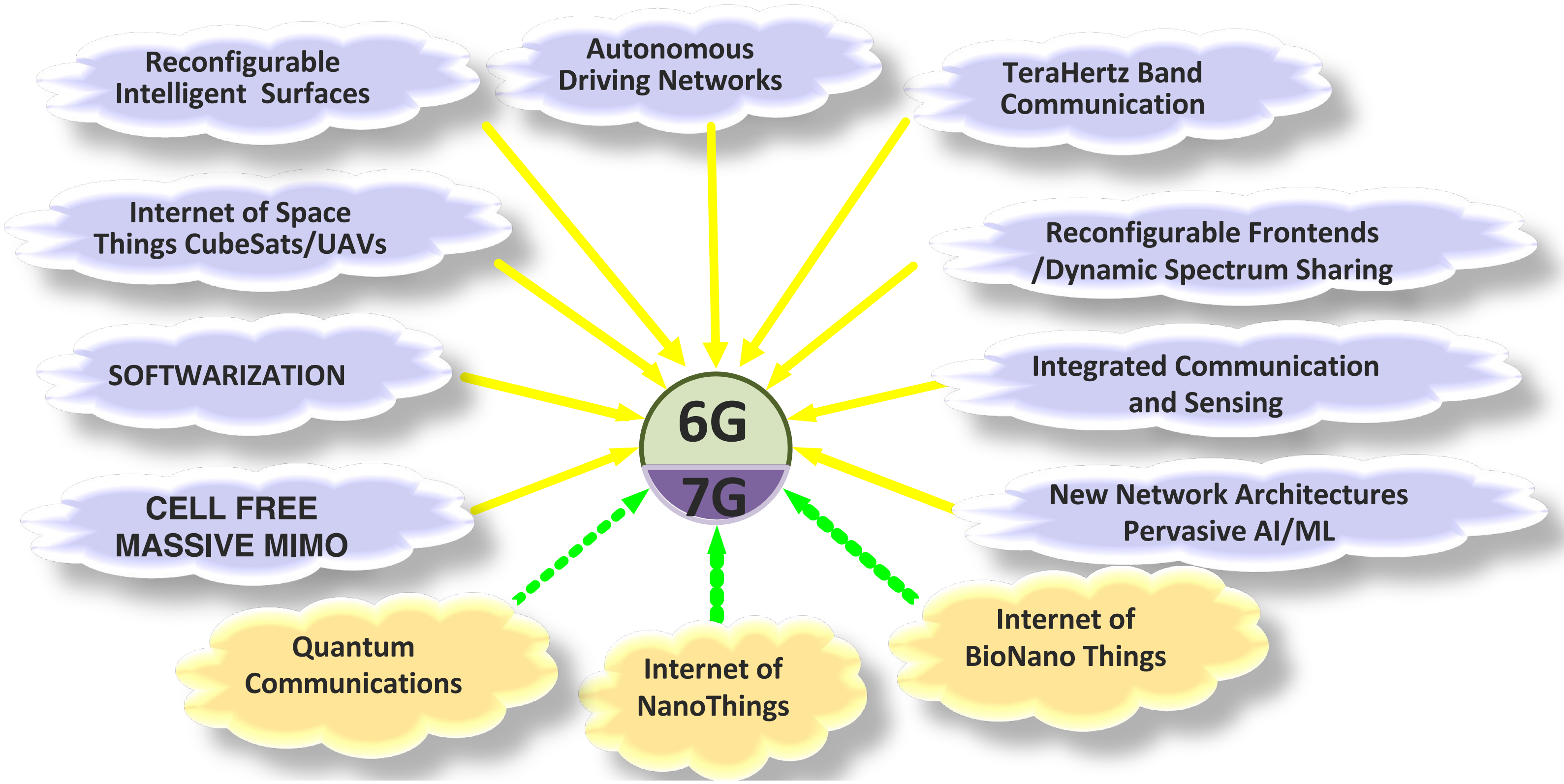
International Telecommunication Union (ITU)
ian.akyildiz@itu.int

NETWORKING 2030-2040

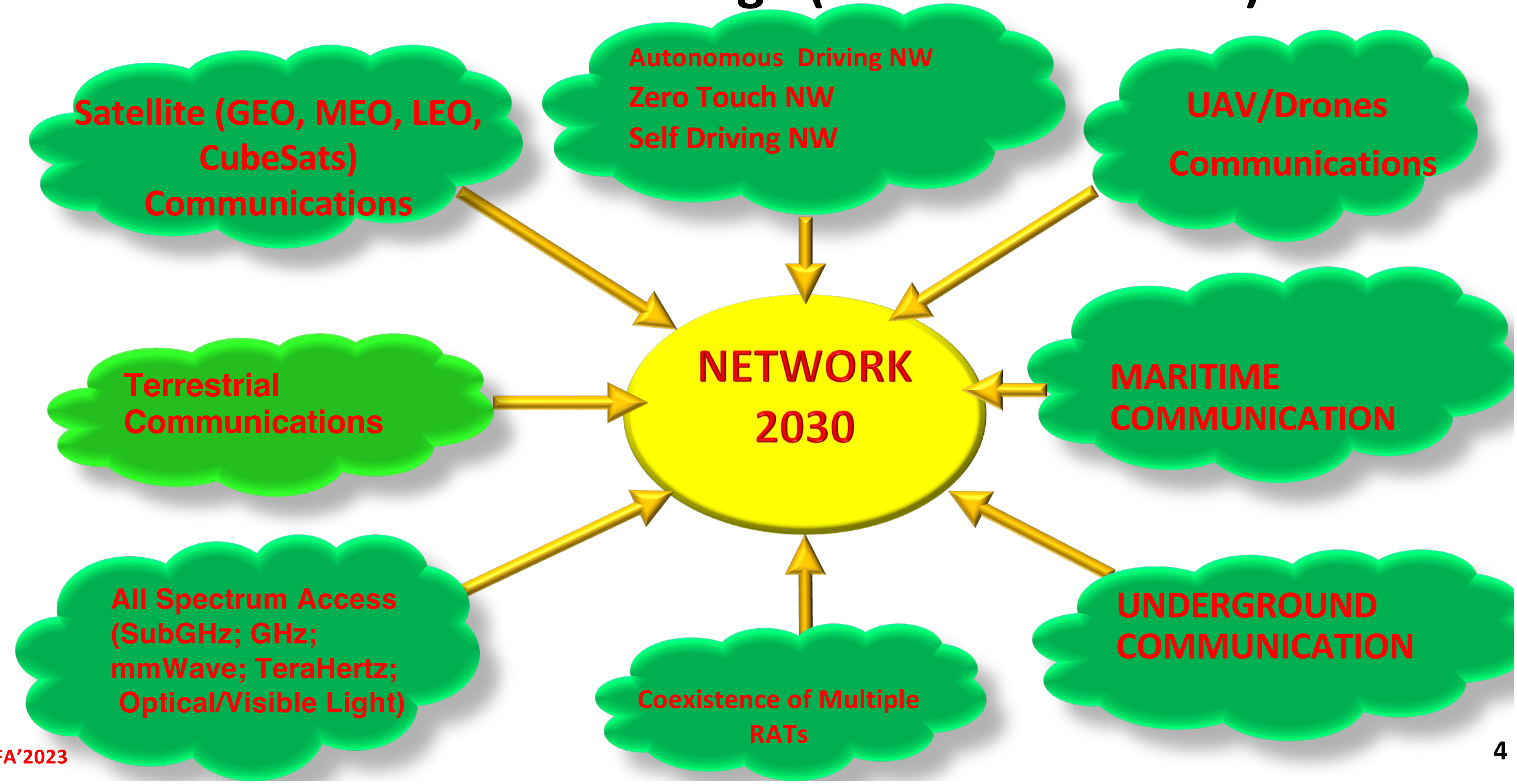


Key Enabling Technologies for 6G and BEYOND

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.



2030 Global Coverage (3D NETWORKING)



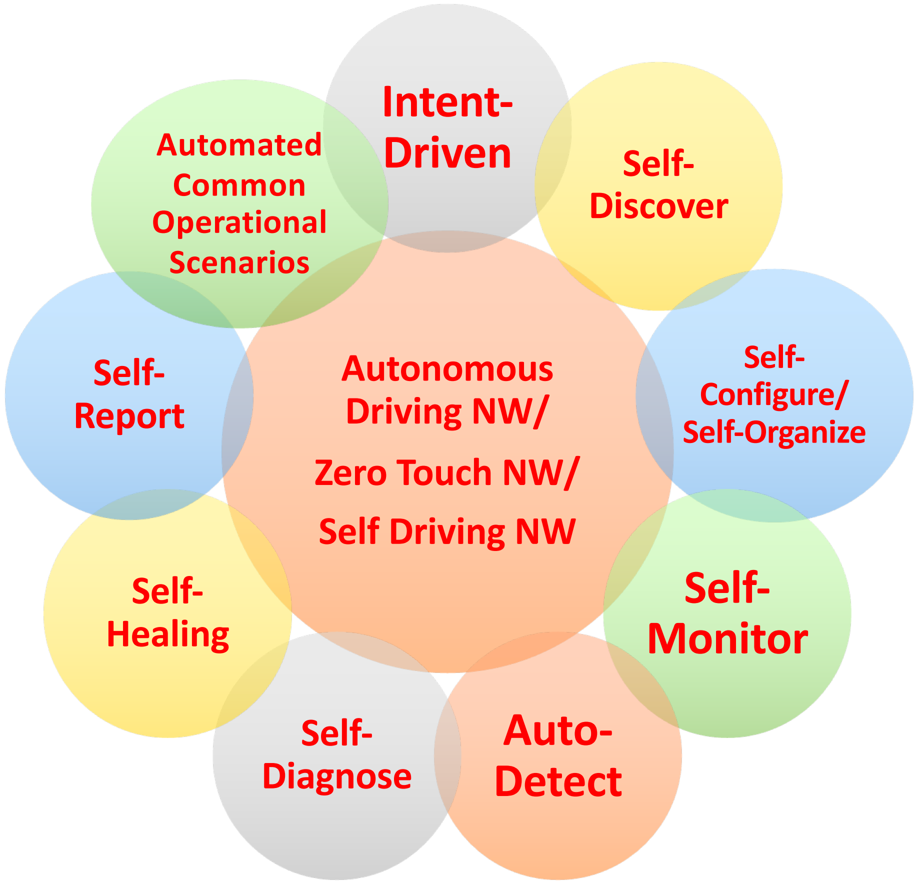
Fully Autonomous Networks Without Human Intervention

WHY?

* Networks are growing year by year, but OPEX is growing faster than revenue.

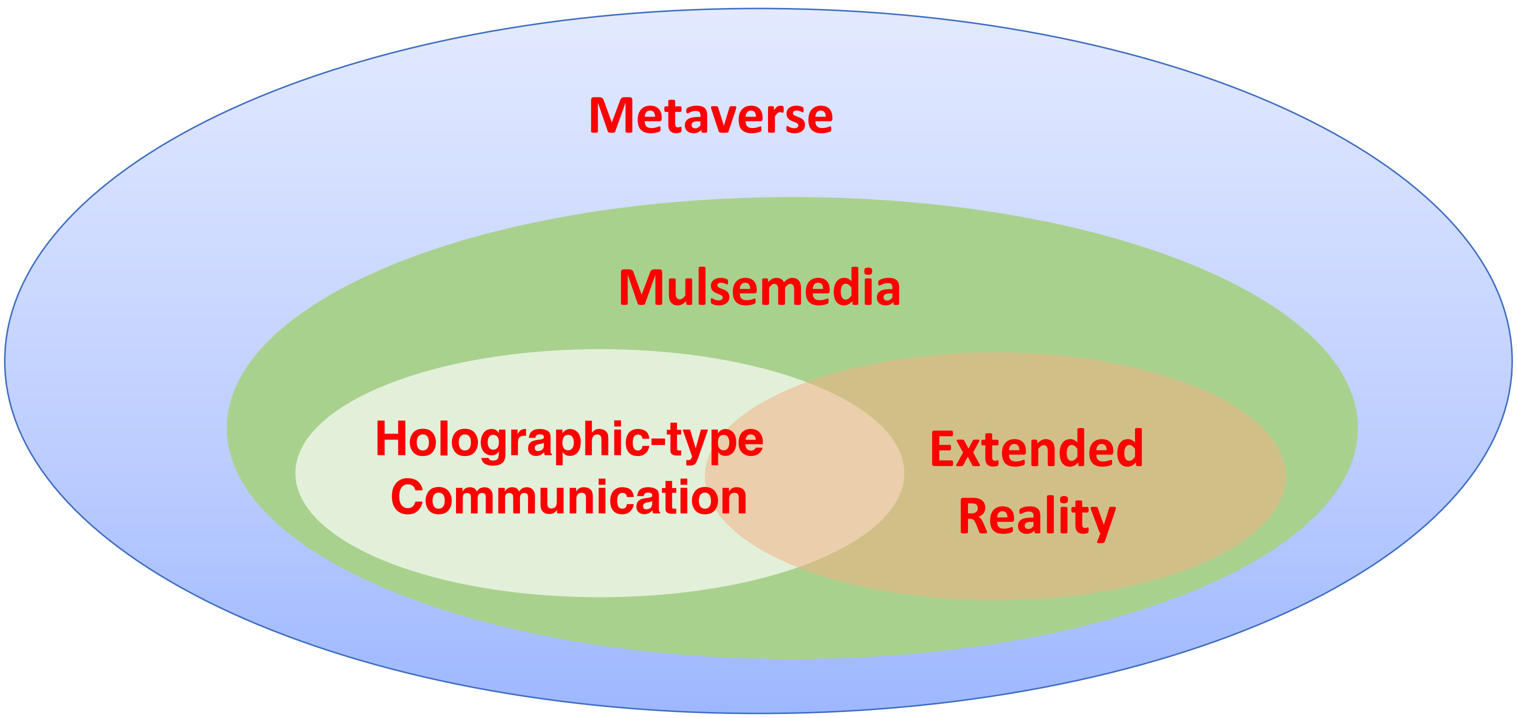
- It takes 100 times more effort for telecom operators to maintain their networks than OTT players.

→ Build Autonomous Networks!



SERVICES

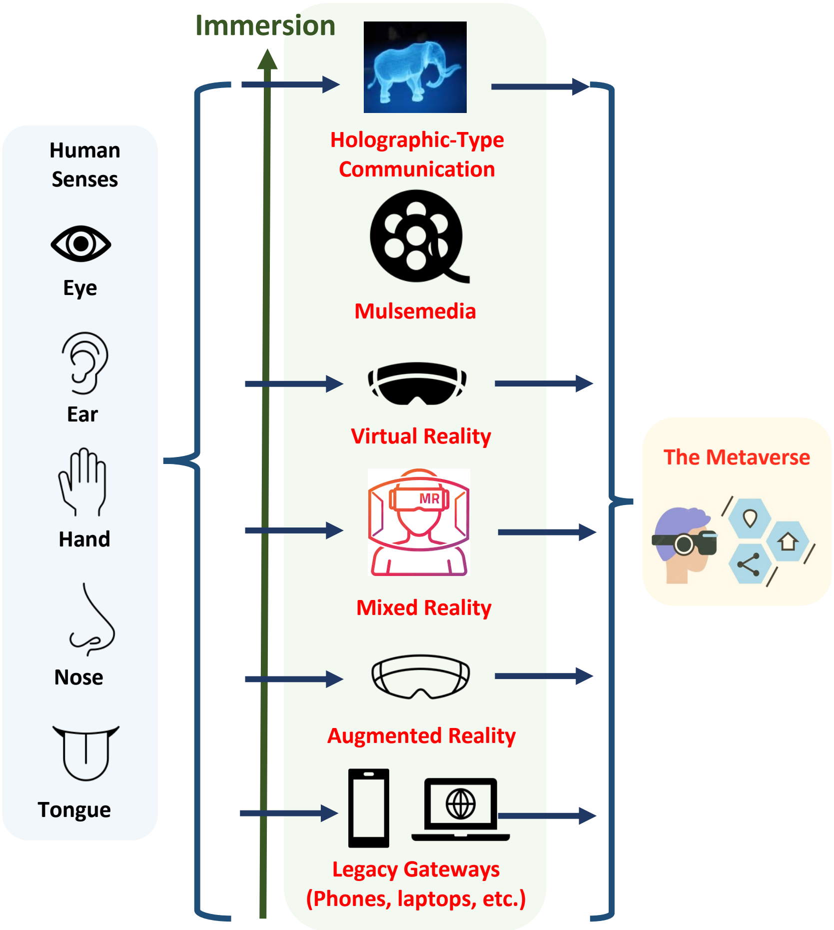
- I.F. Akyildiz and H. Guo, "Wireless Extended Reality (XR): Challenges and New Research Directions", ITU J-FET journal, April 2022.
- I.F. Akyildiz and H. Guo, "Hologram Type Communication: A New Challenge for the Next Decade", ITU-J-FET journal, September 2022
- I.F. Akyildiz, H. Guo, A. R. Dai and W. Gerstacker, "Mulsemedia Communication Research Challenges", ITU J FET, Fall 2023.



What Is Metaverse?

- "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)

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



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

- MULSEMEDIA COMMUNICATION

Web3.0

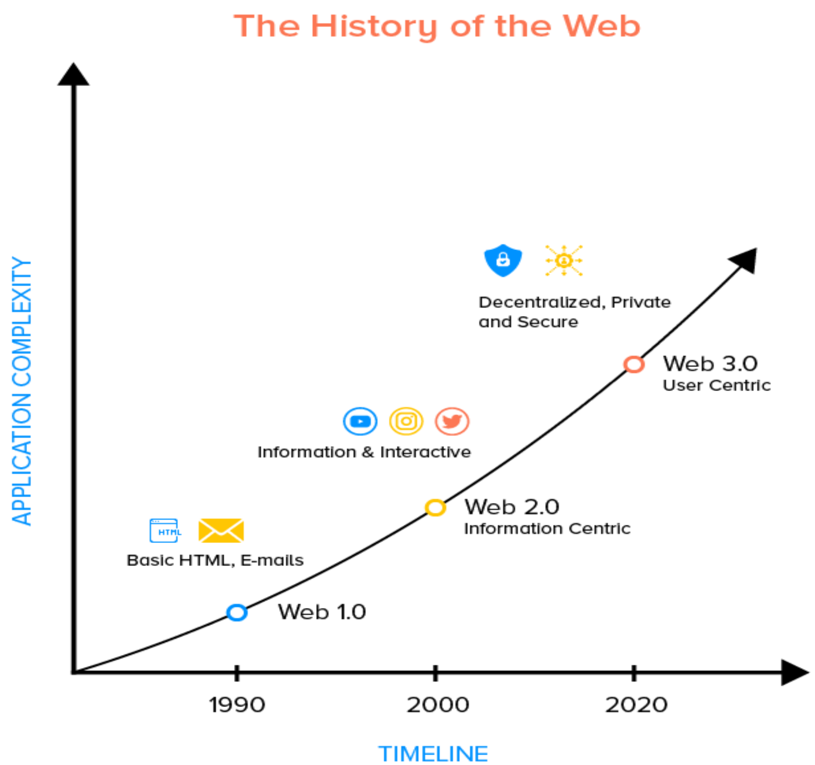
- Decentralized & Autonomous
- Heavily based on AI/ML
- Blockchain-based Technologies
- Cryptocurrency Enabled
- Intelligent and Adaptive Apps
- Semantic Technologies

Metaverse Worlds (more than 10K)

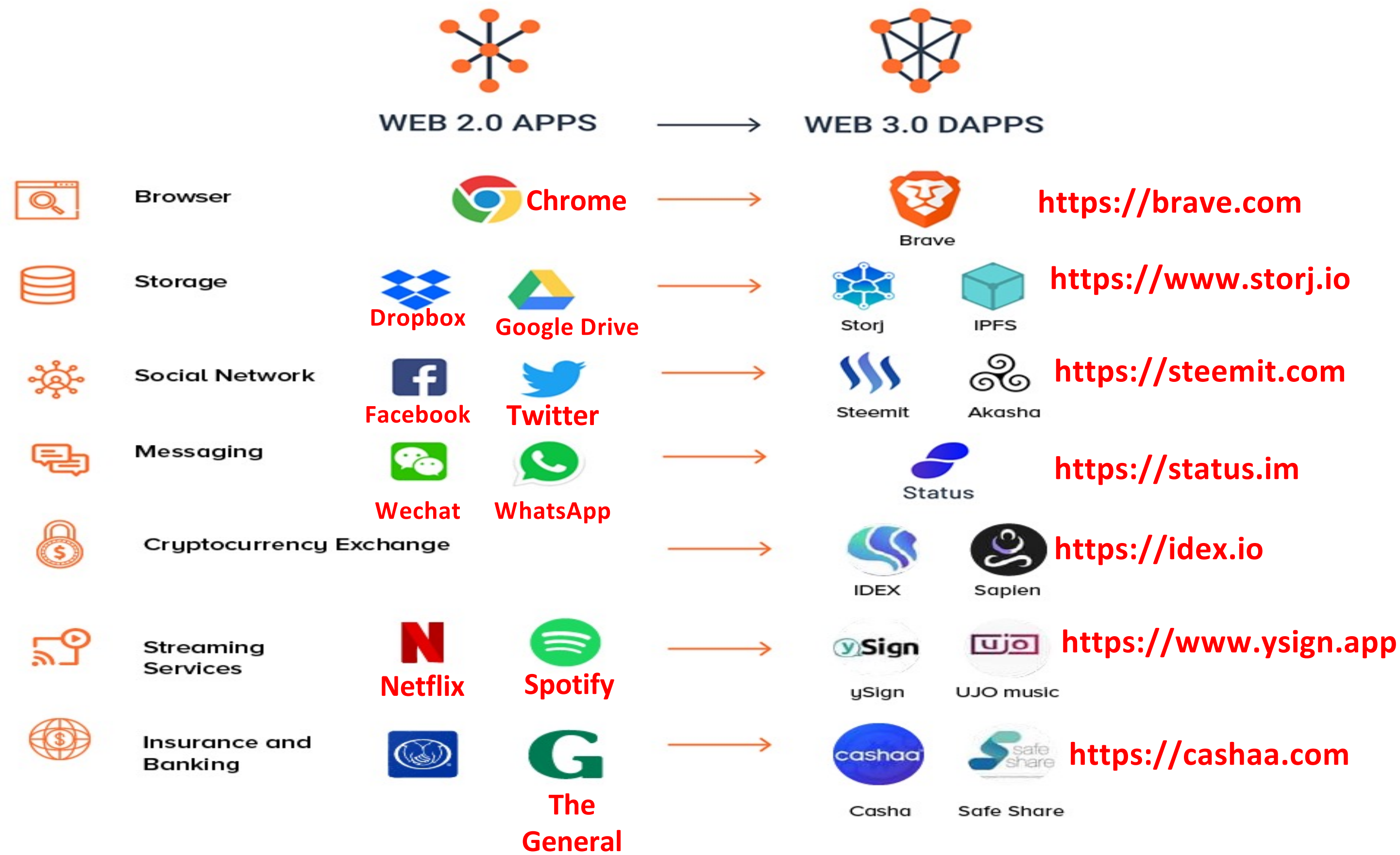
- **Decentraland**
  (2015: Argentina; one of the hottest Virtual World; Divided into plots of land and themed neighborhoods that users can explore. Starting price: 13$K; Genesisplaza, Fashion District to Vegas City and District X)
- **Robbox**
  (Platform for many other games; 200 Million games on its platform; Developers make 1M$/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



Metaverse Market

Virtual-Asset Economy

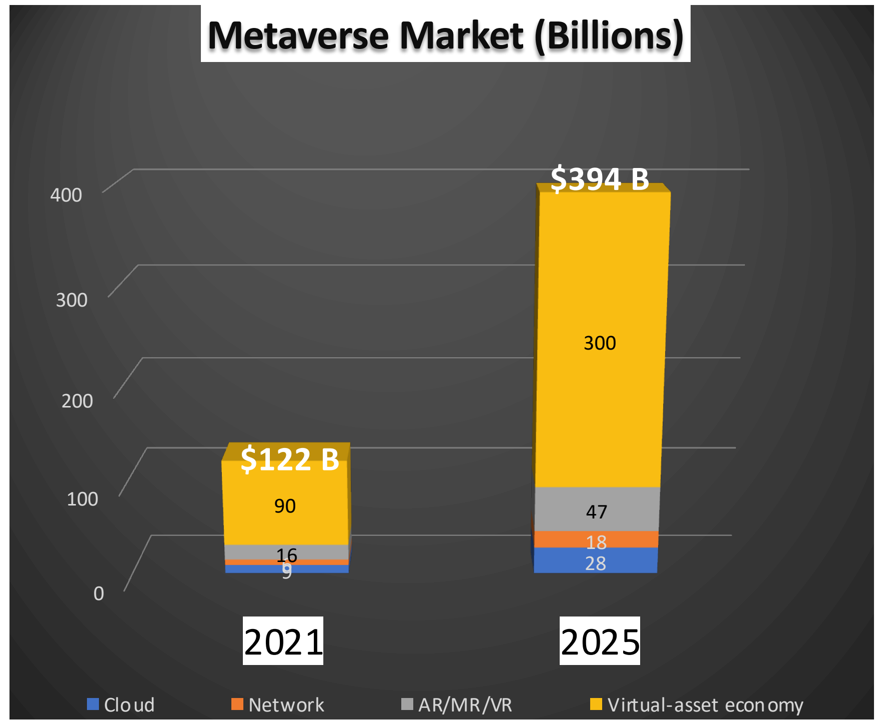
XR/HTC/MM
- Hardware
- Software
- Mobile Ads

Requires Bandwidth & Cloud

Networks and Cloud Infrastructure

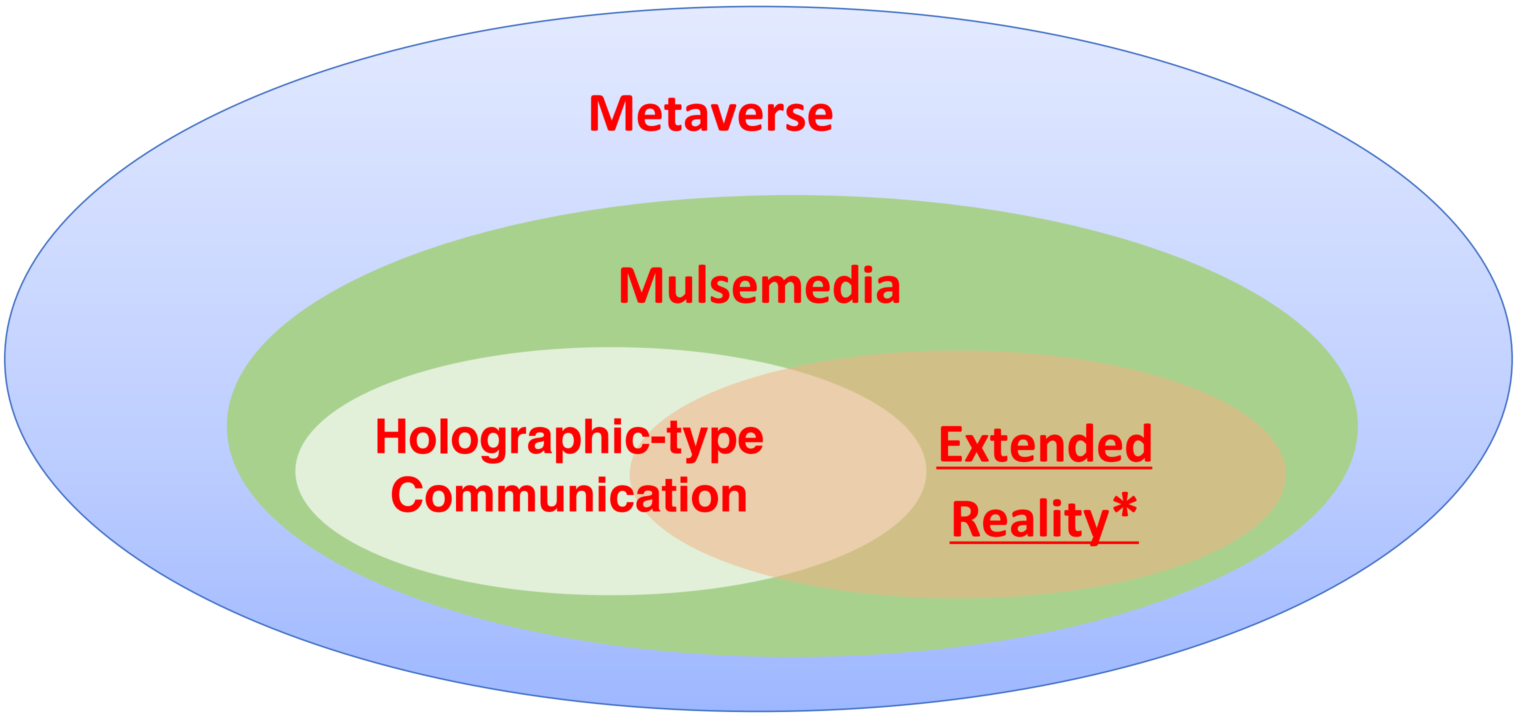
Existing PC, Mobile, and Tablet Hardware and Software

Existing Blockchain Network and Cloud Infrastructure



SERVICES

- 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
- I.F. Akyildiz, H. Guo, A.R. Dai and W. Gerstacker, "Mulsemedia Communication Research Challenges", ITU J FET, Fall 2023.



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.

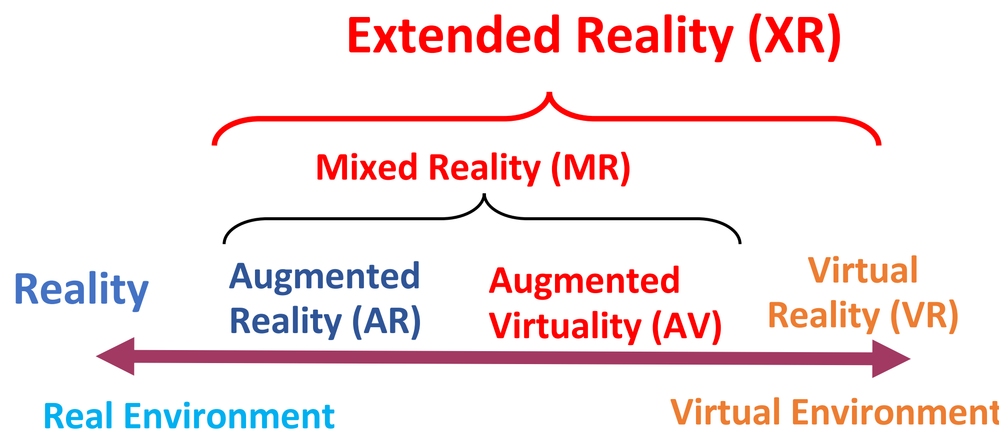
P. Milgram and F. Kishino,
"A Taxonomy of Mixed Reality Visual Displays"
IEICE TRANSACTIONS on Information and Systems, 1994.

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

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

XR → Overarching term for AR and VR

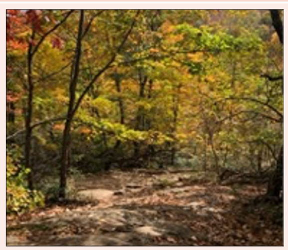
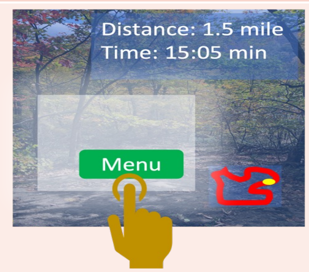
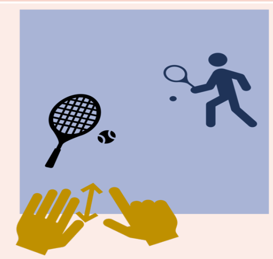
- **AR: Real environment is augmented with virtual objects and information**
- **VR: Fully virtual environments & objects**



Reality-Virtuality Continuum

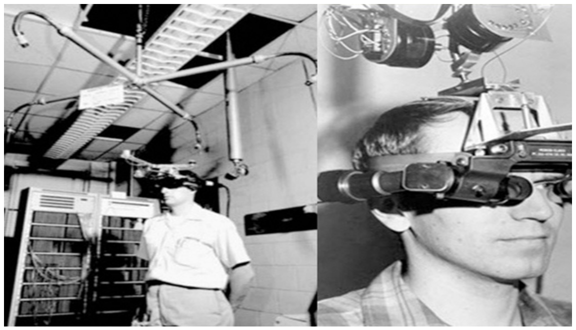
New techs AI/ML, IoT, 5G/6G, make these realities possible !

Devices & Use Cases

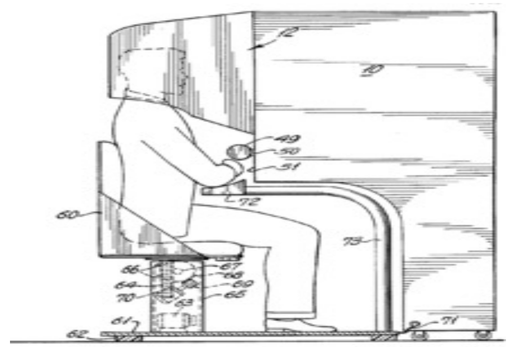
		Extended Reality (XR)		
	Reality	Augmented Reality (AR)	Mixed Reality (MR)	Virtual Reality (VR)
Display	Naked Eye/Optical Glasses	Translucent Display	Translucent Display	Occlusion Display
Display Example				
Example	 Real View of a Trail	 Augmented Virtual Map and Direction	 Interactive Virtual Contents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

Then & Now

Sword of Damocles AR (1968)

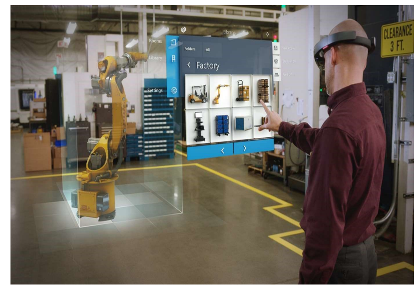


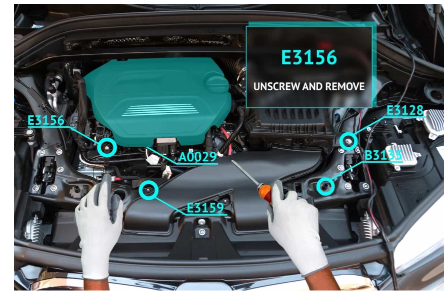
Sensorama VR (1962)



Use Cases

- **Entertainment, sports, health care, tourism, education and e-commerce, etc.**
- **Automotive Industry**
- **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	–





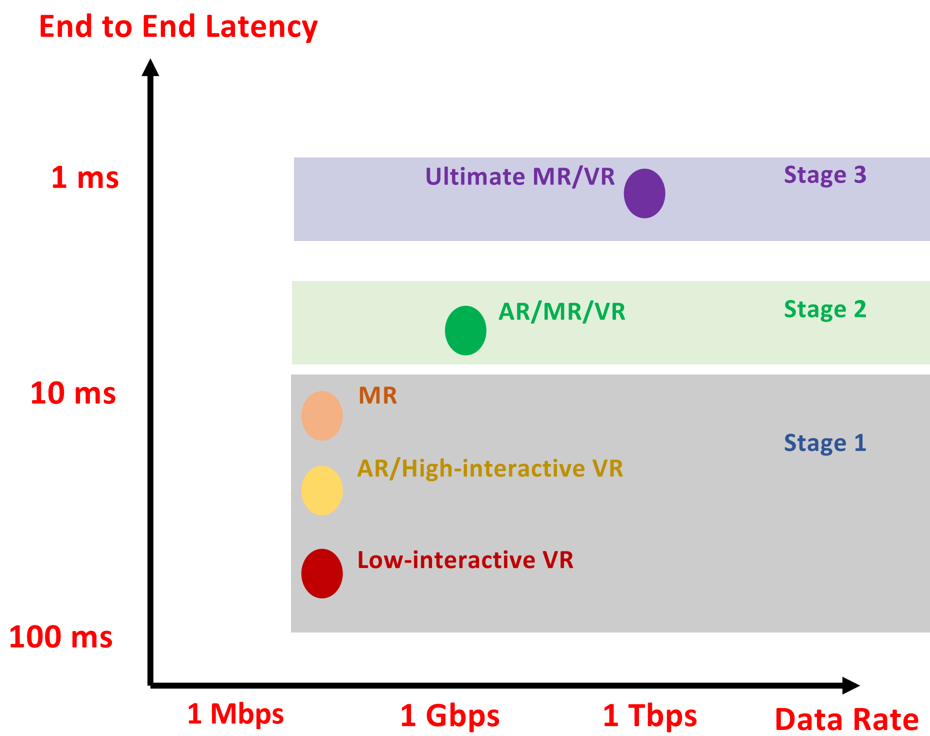


XR Devices: Future

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

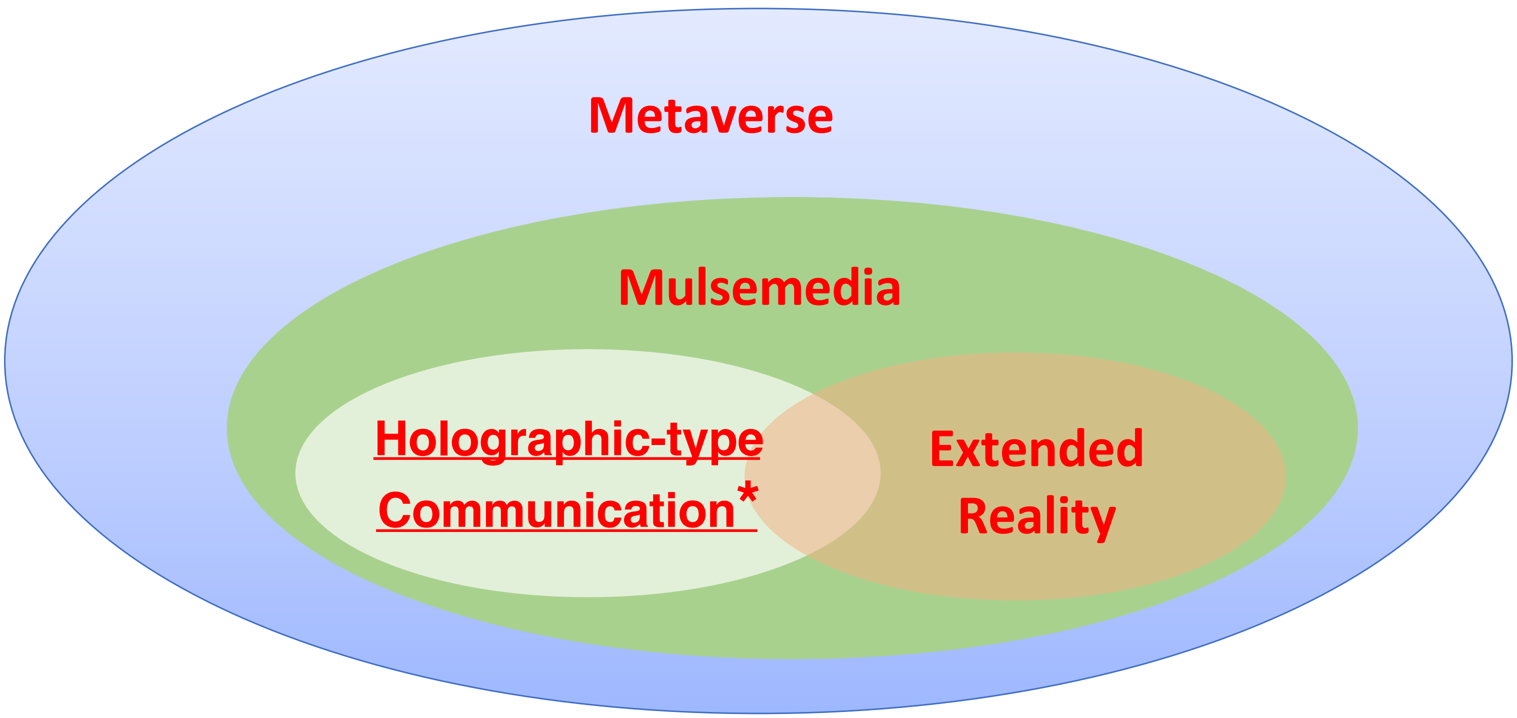
- Untethered wireless headsets
- Lightweight headsets
- High-quality content
- Mobility support

Future: Ultimate XR



SERVICES

- 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
- I.F. Akyildiz, H. Guo, A.R. Dai and W. Gerstacker, “Mulsemedia Communication Research Challenges”, ITU J FET, Fall 2023.

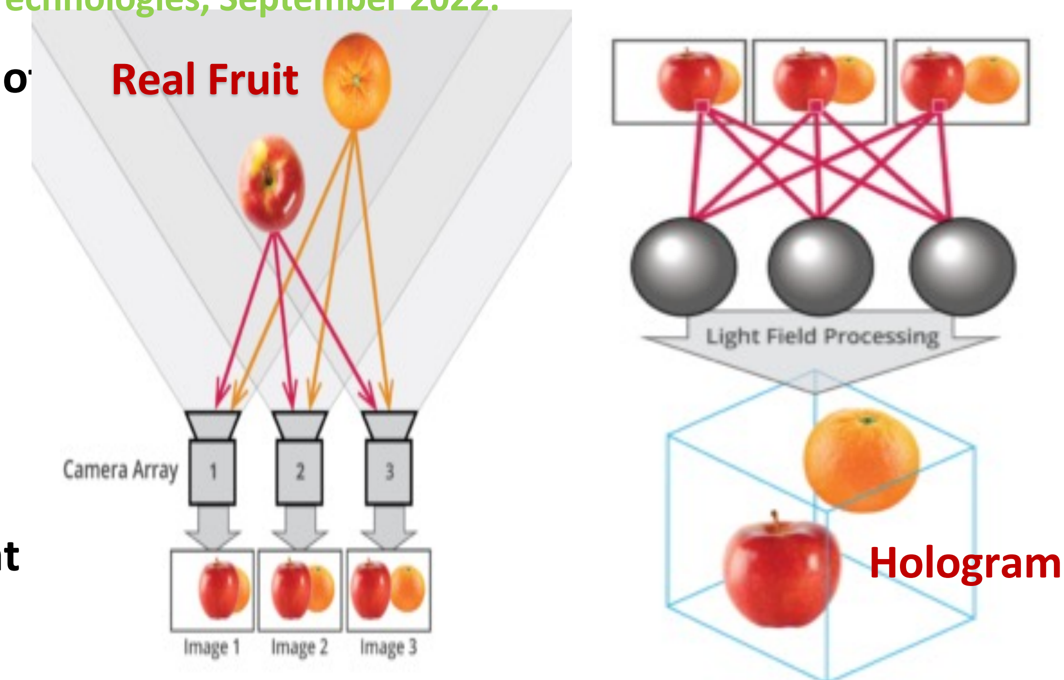


HOLOGRAM

I.F. Akyildiz and H. Guo,
"Hologram Type Communication: A New Challenge for the Next Decade",
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

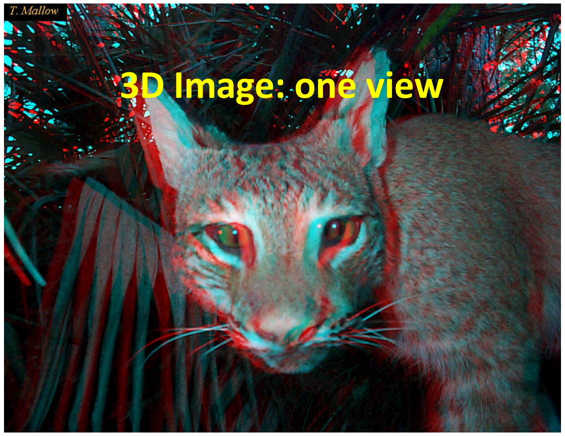
- Holography is a photographic technique that records the light scattered from an object, and then presents it in a way that appears 3D



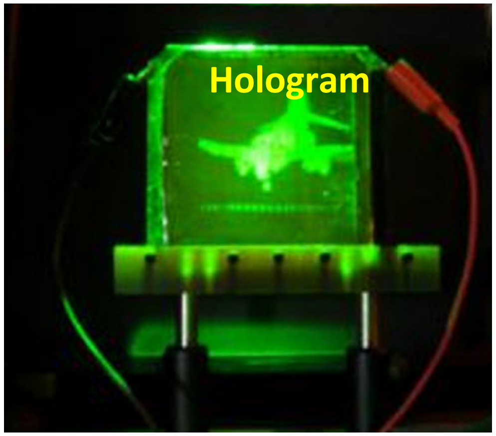
Source: lightfield-forum.com/what-is-the-lightfield/

Differences between Hologram and 3D Content

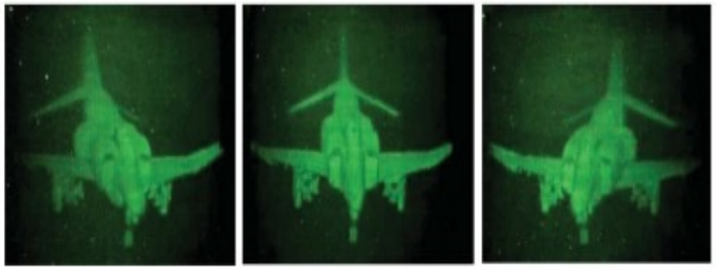
- 3D image is formed by two 2D static views of the same scene (left and right eyes)
- The image is the same regardless of the viewer's position
- Hologram adds parallax, i.e., the viewer can interact with the image → 'User Interactivity Challenge"



Source: Wonderful Engineering



Source: www.kurzweilai.net



Different view angles observe different 3D images

Use Cases for HTC

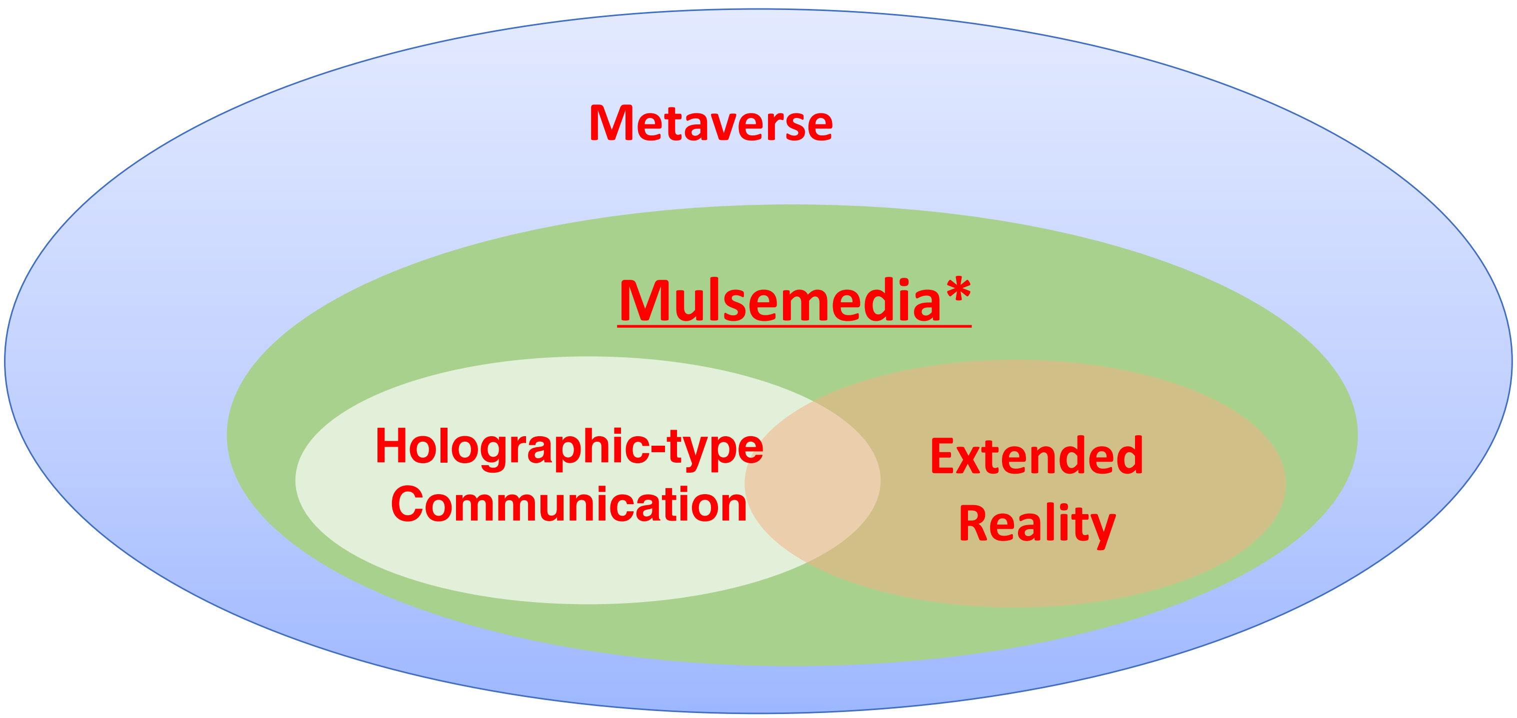
- Earliest: "Telehuman" in 2012
- Near-real person video conferencing
- High resolution remote sensing in challenged areas
- Live sports broadcast using holograms
- Holograms in Education; Conferences etc.

bigthink.com

eu-startups.com

SERVICES

- 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
- I.F. Akyildiz, H. Guo, A.R. Dai and W. Gerstacker, "Mulsemedia Communication Research Challenges", ITU J FET, Fall 2023.



HTC and 5 Senses

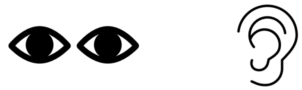
- **HTC is not only about hologram**
- **HTC operates in a true 3D space, and leverages all 5 senses:**

  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 vs Multimedia

Multimedia = Video + Audio



Mulsemedia = Video + Audio + Haptic + Gustatory + Olfactory + …

- **Mulsemedia: Multi-Sensory Media**
  - **Media that includes more than two senses**
  - **More senses: balance, moisture, wind, ambient light, etc.**

*** "Multimedia" was coined by singer and artist Bob Goldstein to promote the July 1966 opening of his "Lightworks at L'Oursin" show NYC.**

*** "MULSEMEDIA= MULti Sensory MEDIA" was coined by Gheorgita Ghinea in 2010.**

EVOLUTION OF MULSEMEDIA SYSTEMS

Mein Traum	Tingler	Behind the Great Wall	Scent of Mystery	Sensorium	iSmell	4DX	OVR Technology
Film	Film	Film	Film	Film	Digital Scent	4D Film Format	Digital Scent
1940	1959	1959	1960	1984	1999	2009	2020
Scent	Vibration	Scent	Scent	Vibration/Scent	Scent	Multiple Senses	Scent
"Smell-o-Dramma" released 32 different odors into the theater	"Percepto" buzzers underneath seats	"Aroma Rama" scents through AC into the theater	"Smell-o-Vision" pumps scents out of vents beneath seats	first 4D film with bodysonic seats and scent-a-vision	controlled by computers & various scents are generated	multi-sensory effects, incl. motion seats, wind, light, senses	scent devices can be connected to XR headsets to generate senses

MULSEMEDIA DEVICES

E.B. Saleme, A. Covaci, G. Mesfin, C.A. Santos, and G. Ghinea,
"Mulsemedia DIY: A Survey of Devices and a Tutorial for Building your own Mulsemedia Environment",
ACM Computing Surveys, 2019.

Mulsemedia production (haptic, auditory, visual, olfactory, gustative, air flow, water jet effects)

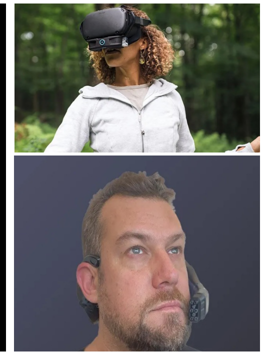
Touch Sensors & Displays

Gloves can sense hand motions and provide feedback!
Touch sensor and touch display!

Sense	Name	Sensor/ Display	Year	Description
Haptic	Touch from 3D Systems	Sensor & Display	2014	User can manipulate on-screen 3D objects and feel force feedback on their hands.
	MANUS Haptic VR Gloves	Sensor & Display	2014	Interact with virtual models and generate haptic feedback.

Smell Sensors & Displays

VR smell display



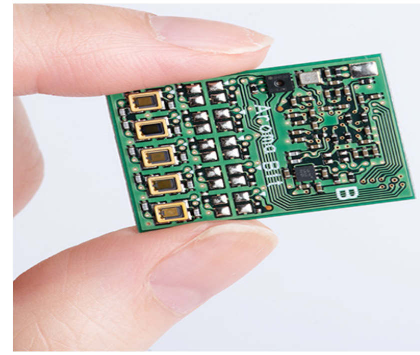


Image: Madeleine Smell Camera

Image: OVR ION

Aroma bit: digital smell sensor array

Sense	Name	Sensor/ Display	Year	Description
Olfactory	Madeleine "Smell Camera"	Sensor	2013	Record odors and generate scentography.
	OVR ION	Display	2020	Wearable wireless digital scent generator.
	Olorama	Display	2013	Stimulate the sense of smell using more than 200 different scents.

Taste Sensors & Displays

N. Ranasinghe, and E. Yi-Luen Do. **"Digital lollipop: Studying electrical stimulation on the human tongue to simulate taste sensations"** ACM Trans. on Multimedia Computing, Communications, and Applications (TOMM), (2016)

H. Miyashita, **"Norimaki synthesizer: taste display using ion electrophoresis in five gels"** 2020 CHI Conference on Human Factors in Computing Systems. 2020.

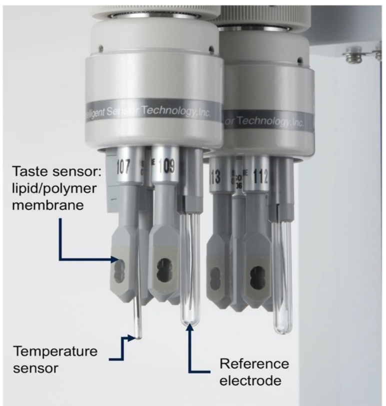


Image: e-Tongue by Insent

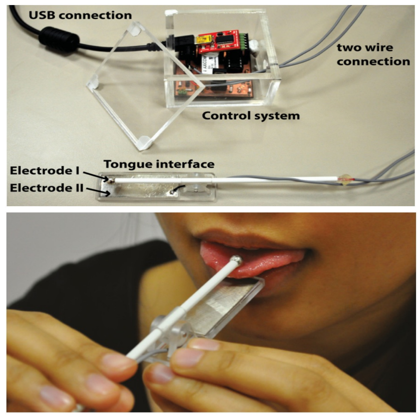
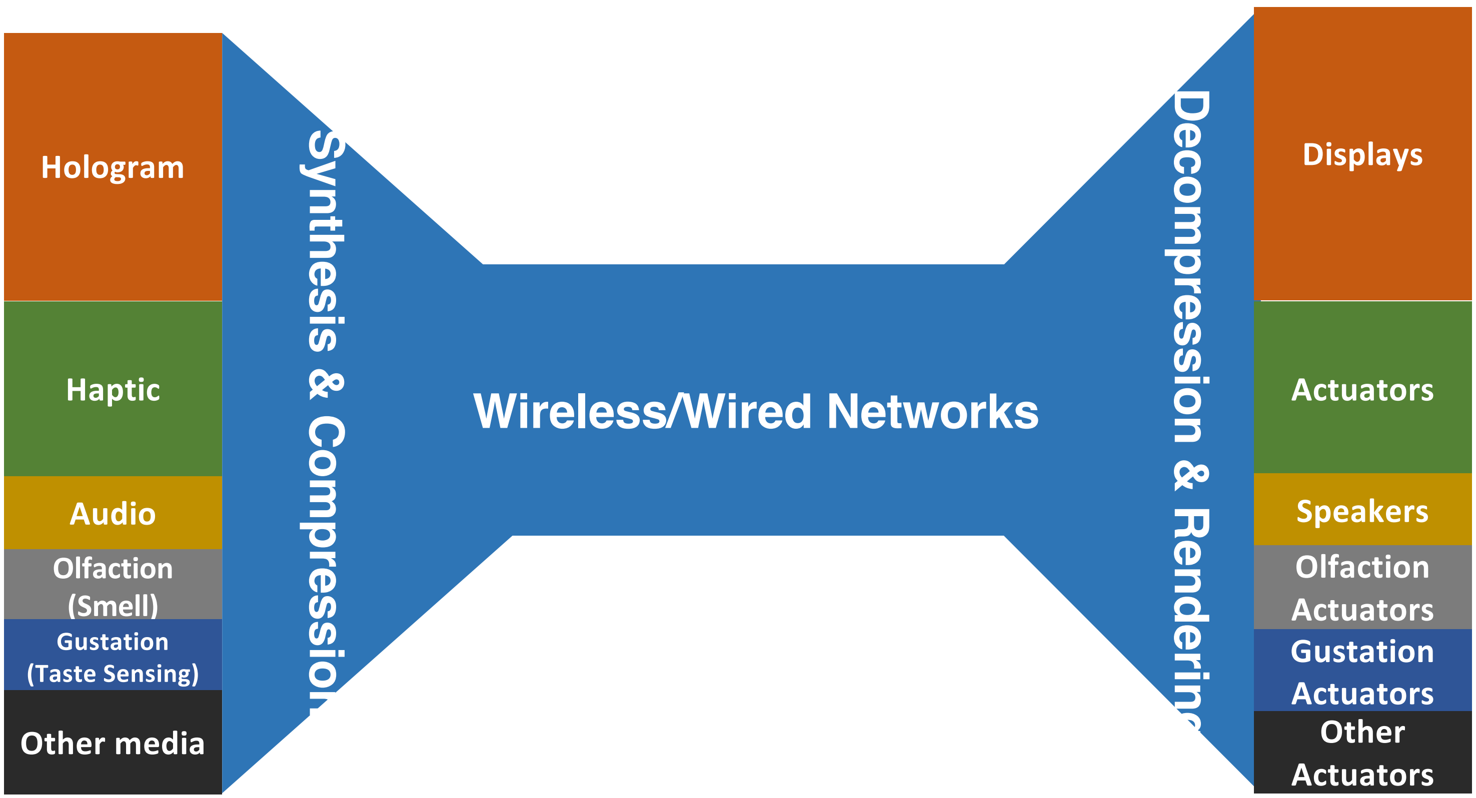


Image: Digital Lollipop

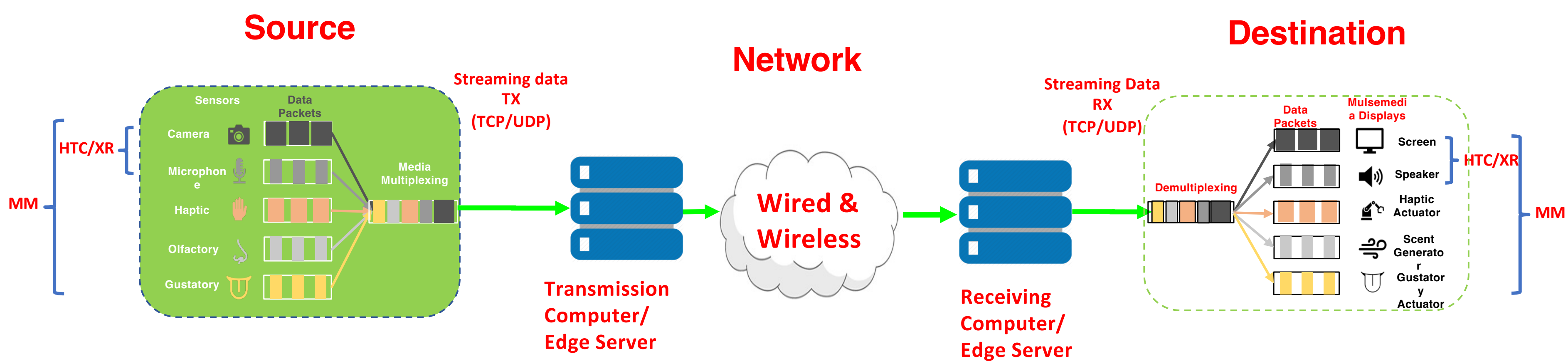
Image: Norimaki Synthesizer

Sense	Name	Sensor/ Display	Year	Description
Gustatory	e-Tongue by Insent	Sensor	1993	A sensor system using biomimetic membrane to provide high sensitivity of gustatory signals.
	Digital Lollipop	Display	2016	Digitally stimulate gustation using electric currents on the human tongue.
	Norimaki Synthesizer	Display	2020	Using electrolytes to supply mixed five basic tastes and generate arbitrary taste to the user's tongue.

XR/HTC/Mulsemedia Communication

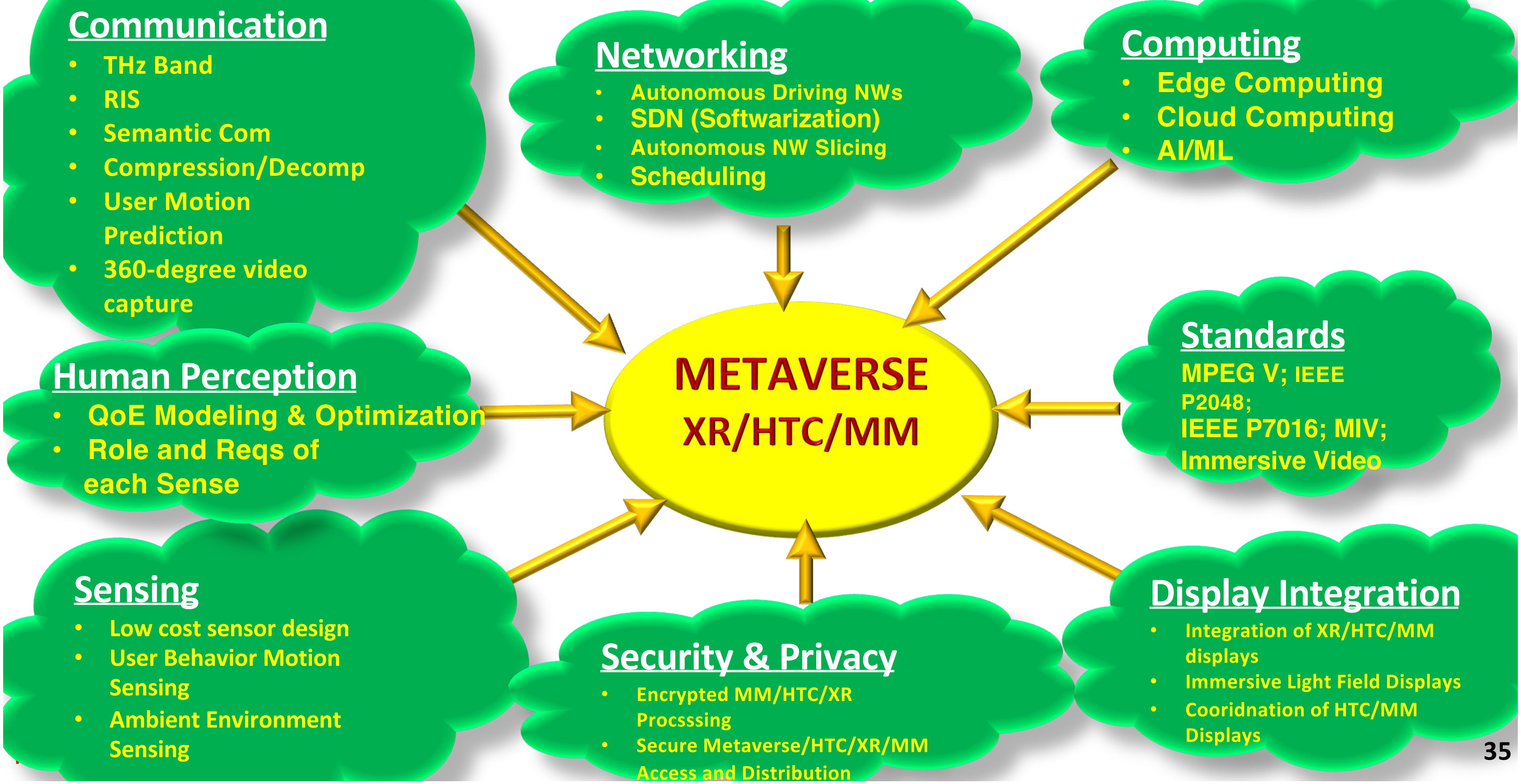


XR/HTC/MM Communication Systems

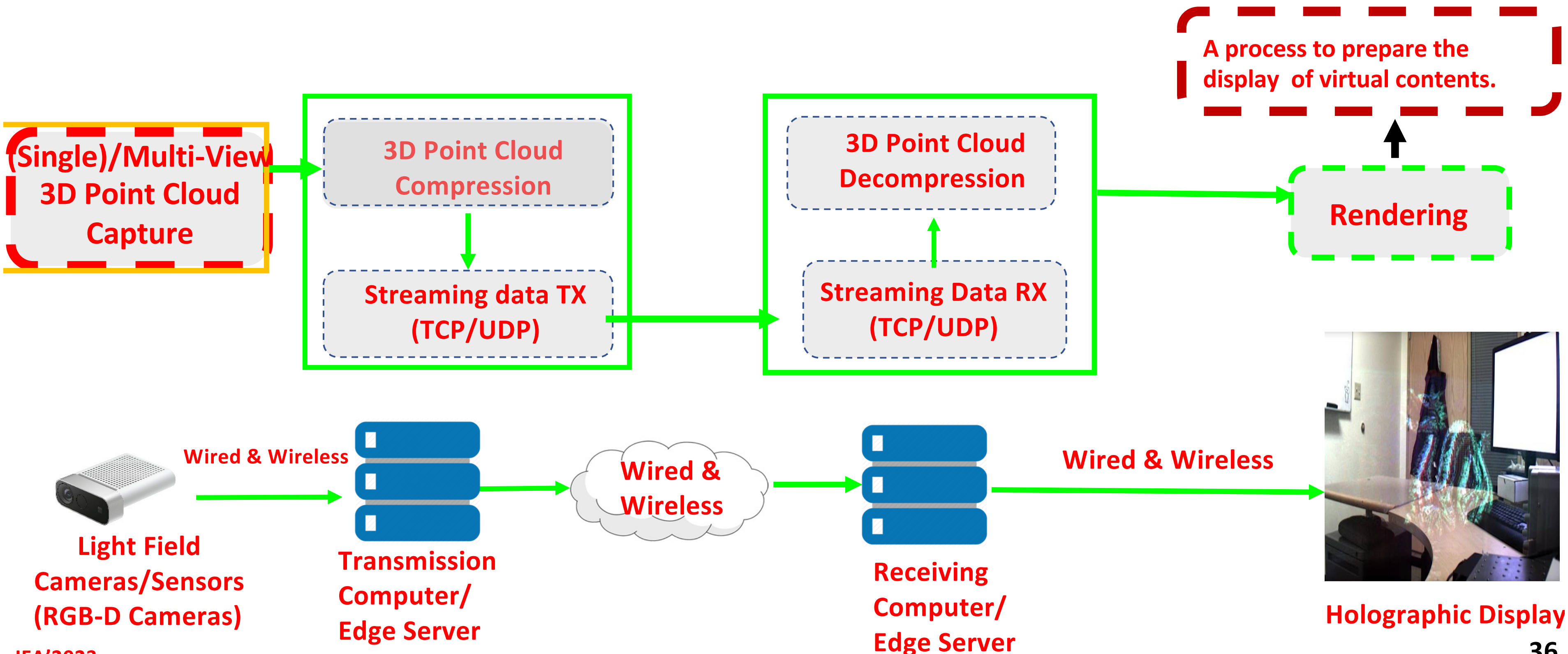


IFA'2023

Research Challenges



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)

Light Field Cameras
Source: Road to VR

Multiview Images

- **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

Tradeoff:

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

Point Cloud Compression: Bandwidth Requirement > 500 Mbps

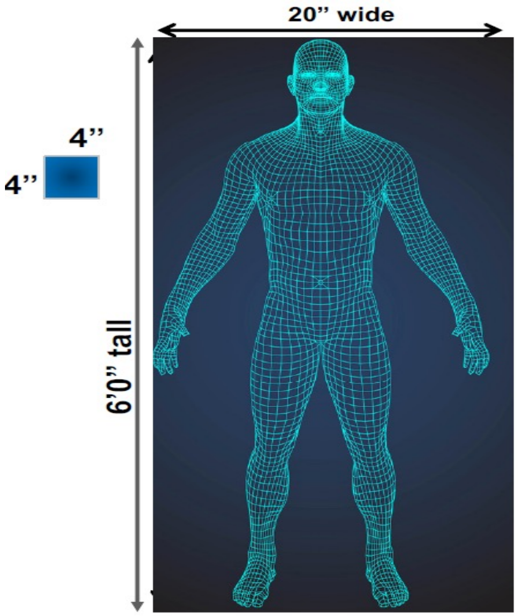
Direct Transmit: Bandwidth Requirement > 1Tbps

1. Source Data Rates

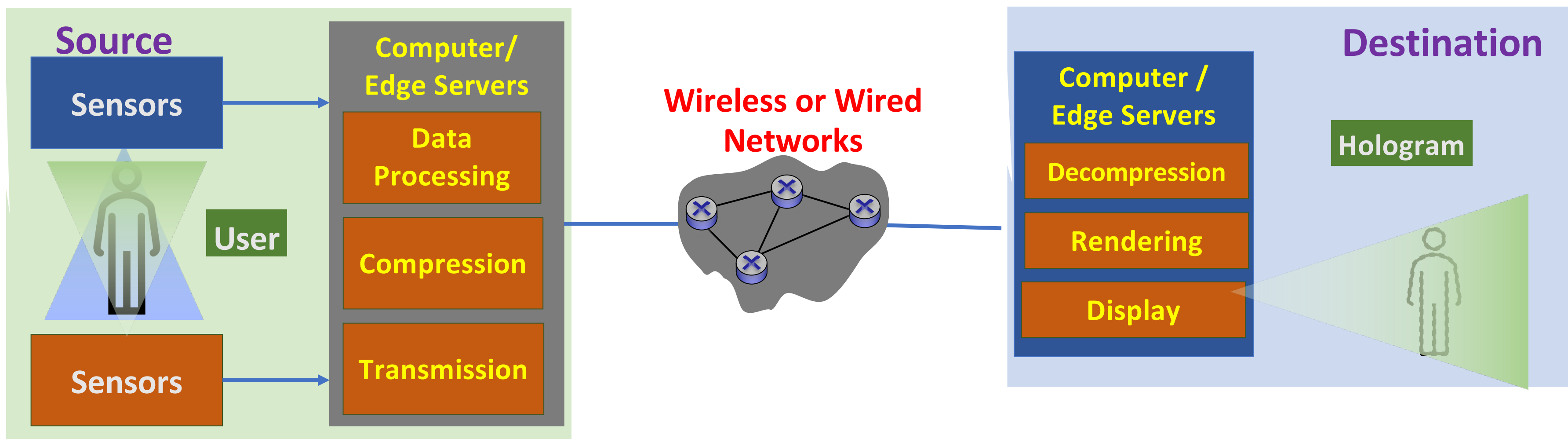
- X. Xu, e. al.
  "3D Holographic Display and Its Data Transmission Requirement."
  IEEE Int. Conf. on Information Photonics and Optical Communications, 2011.
- R. Li
  "Enabling Holographic Media for Future Applications: Identifying the Missing Pieces and Limitations in Networks"
  ACM SIGCOMM 2019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



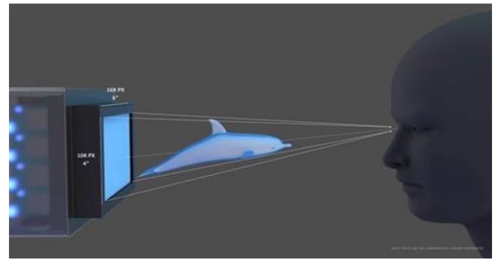
2. Holographic Networks



3. Destination: Holographic Display

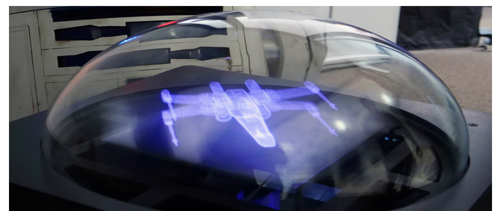
Naked Eyes

Light Field Display
> 1000 Views



Source: fxguide.com

Volumetric Display
> 20 Views



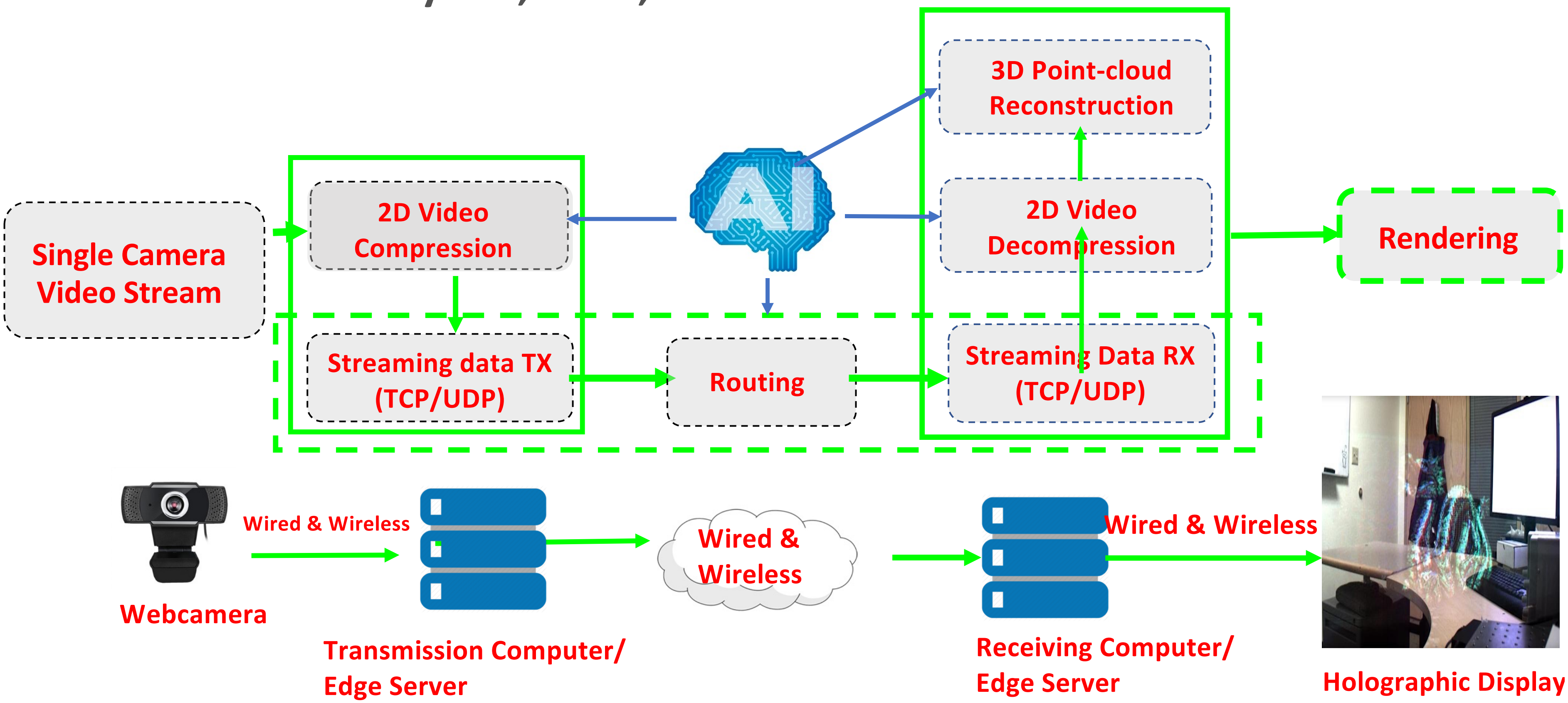
Source: TechEBlog

Extended Reality
Head-Mounted Displays
> 2 Views

2D Display (Cannot display hologram)
1 View

Our Holo4ALL Architecture

I.F. Akyildiz, et.al., 2021-2024



Metaverse Requirements

	Video	VR	MR & AR	Holographic-Type Communication/MM
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

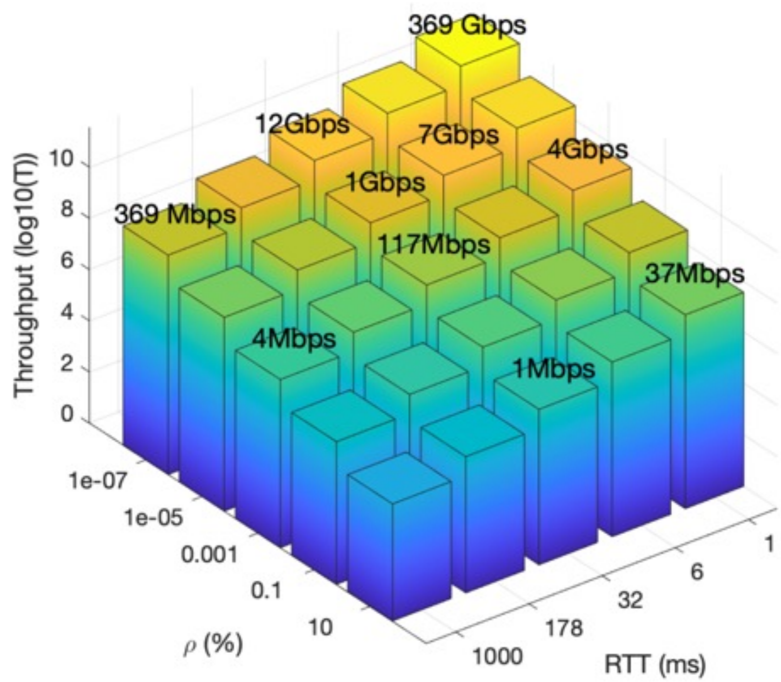
- **Metaverse applications will place significant demands on networking, computing and communication technologies → NOT supported today !**

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**

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 Physical and Data 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**

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

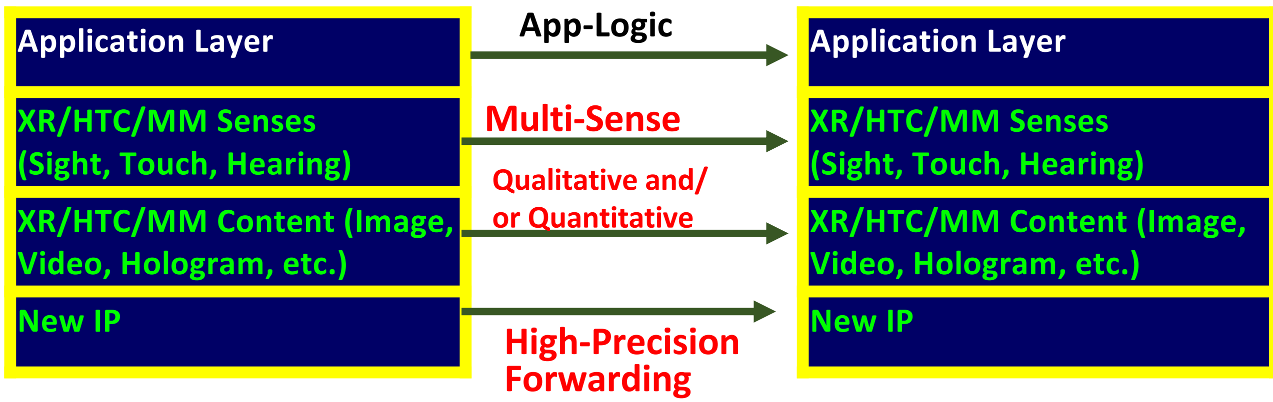
- Pulse-based Modulation ✓
- Multi-band Modulation ✓
- Equalization
- Synchronization ✓
- Ultra-Massive MIMO ✓

THz Networks

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

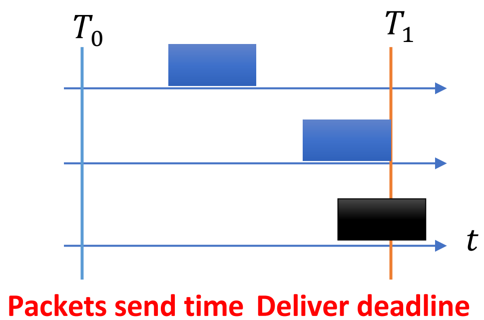
Experimental and Simulation Testbeds

New Protocol Stack

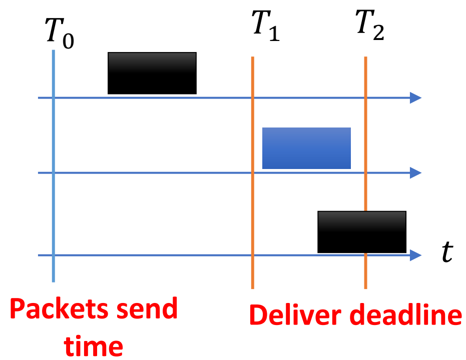


- New IP: A new network protocol to design network architecture, framework and infrastructure with:
  - High-Precision Latency Control
  - Semantic (Quality) Communications
  - Free-Choice Addressing: Not only IPv4 or IPv6

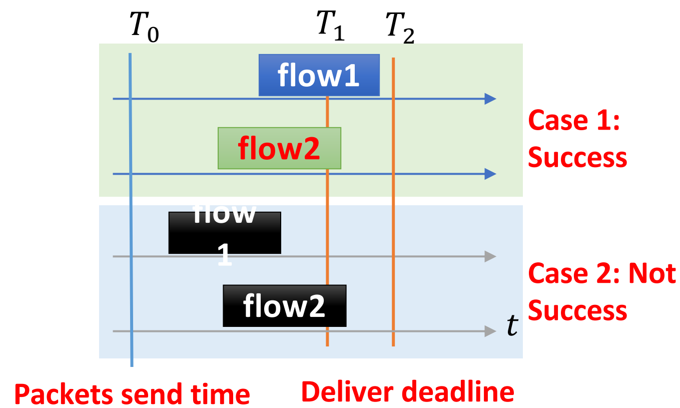
Types of End-to-End Latency Control



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



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

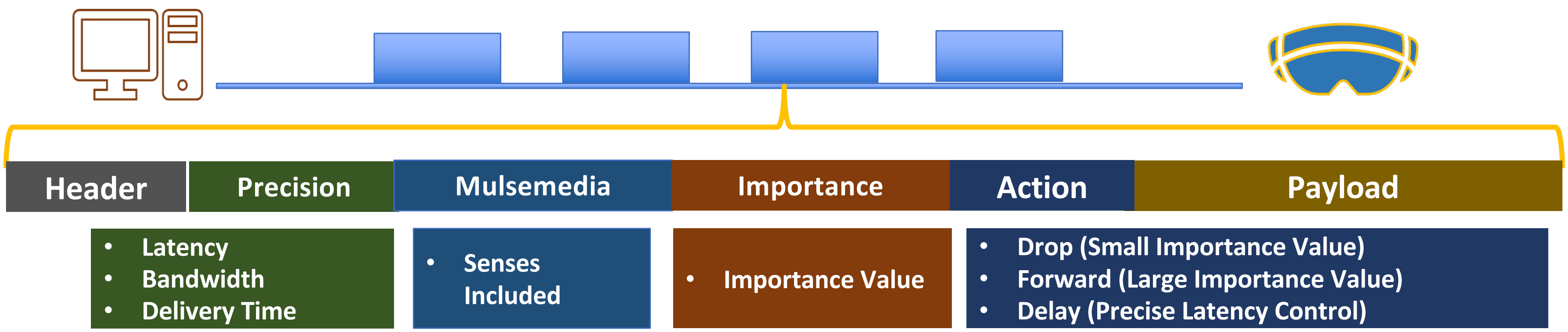


Coordinated Guarantee:
Packets of two or more flows arrive in a coordinated in-time/on-time guaranteed way

- **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**

Packet Wash Protocol

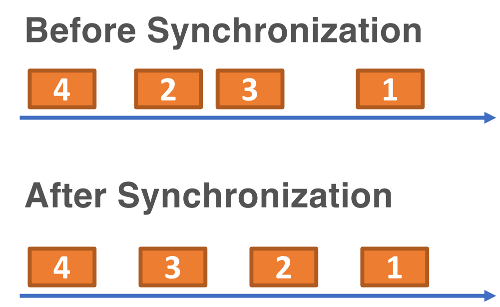
L. Dong, and A. Clemm.
"High-Precision End-to-End Latency Guarantees Using Packet Wash."
Proc. of the IFIP/IEEE Int. Symposium on Integrated Network Management (IM), 2021.



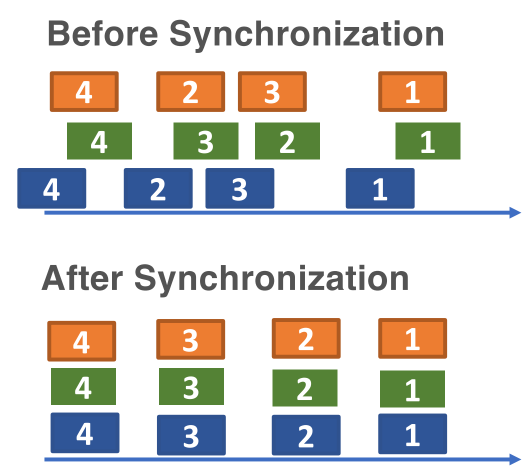
- **Packet Wash:** in presence of network congestion, drop packets that do not significantly affect the QoE (Quality of Experience)
- Drop packets with small importance values instead of dropping all the packets
- Importance value of survived packets should be increased

Media Synchronization

- **Intra-media Synchronization**
  - **The data packets of each sensory media arrive at the destination at different time due to latency, jitter, etc. → misordered**
  - **Use buffer to reorganize each sensory media**

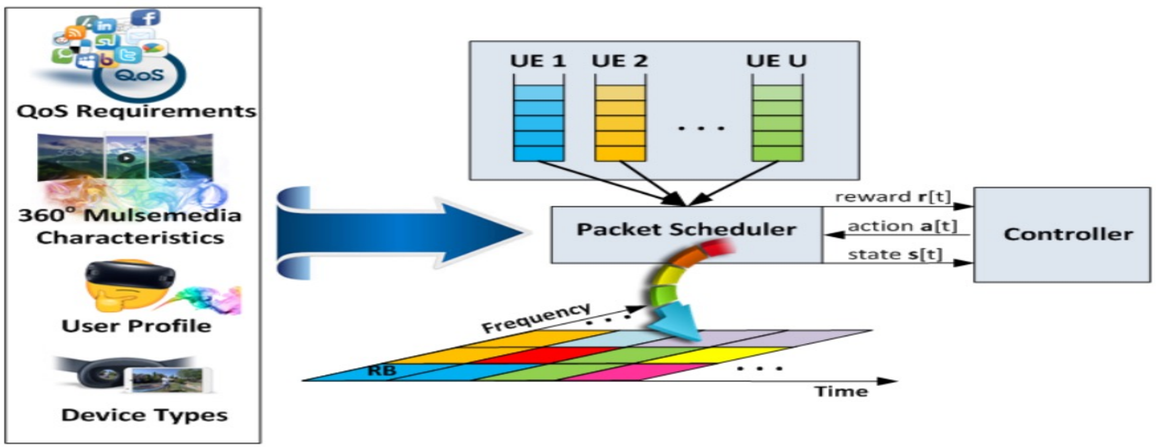


- **Inter-media Synchronization**
  - **Data packets for multiple sensory media need to be synchronized**
  - **The required buffer can be much larger than the intra-media synchronization buffer**
  - **Machine learning can be used to predict missed/delayed sensory media**



Scheduling

C. Ioan-Sorin, R. Trestian, and G. Ghinea.
"360 Mulsemedia Experience over Next Generation Wireless Networks- A Reinforcement Learning Approach"
IEEE 10th Int. Conf. on Quality of Multimedia Experience (QoMEX), 2018.



- Many data sources and queues for 360° video, haptic, olfactory, gustatory, etc.
- Optimal scheduling is required to reduce the end-to-end latency and improve users' Quality-of-Experience
- Reinforcement learning has been adopted to adaptively obtain the optimal scheduling policy.

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.

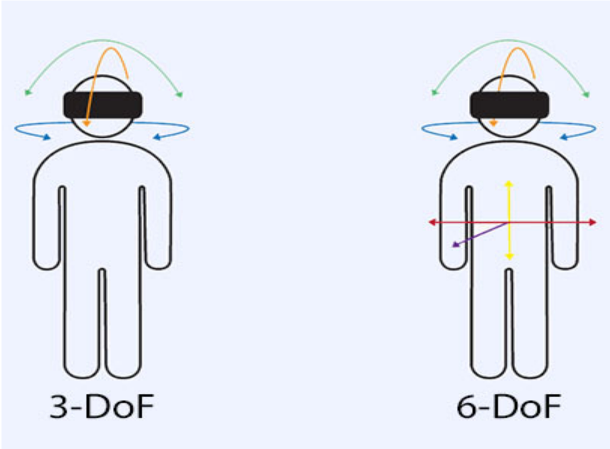
CONTENT GENERATION:

- **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**

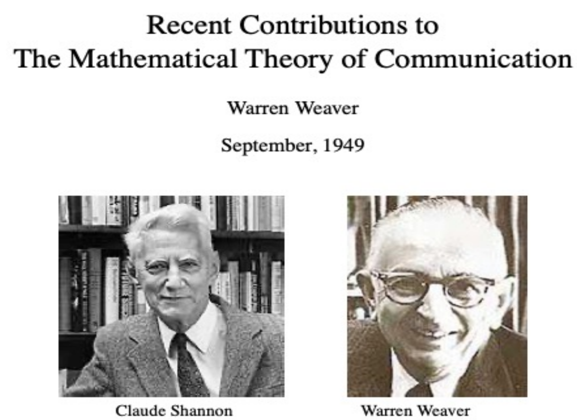
Quantitative Communication vs Semantic (Qualitative) Communication

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



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

- **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 CORRELATION BETWEEN FOR XR/HTC/MM

I.F. Akyildiz, et. al, in preparation, 2023.

- Using deep learning to infer missing senses and improve the robustness of the communication system

Example:
if the source only has cameras and microphones, we can receive only videos and audios

- However, the destination may have scent, wind, and light generators, but the source cannot provide this information.
- Missing information can be obtained by using semantic correlations
- Designing a new semantic-based MM communication system!

OPTIMUS: Limits of Transformers for Semantic Communications

I.F. Akyildiz and S. Tarkoma, Univ. of Helsinki, 2023-2026.

- **Study the effect of the size of neural networks, specifically Transformers**
- **In their performance, i.e. accuracy in various tasks, including natural language processing, and visual question answering**
- **Study the use of Transformers with multi-modal data, i.e. various combinations of text, images, and audio (all senses)**
- **Seek a theoretical foundation (a comprehensive mathematical explanation about the limits of semantic information)**

GOAL:

A better understanding of the semantic limits of Transformers will help to steer the future development of AI-boosted ICT systems.

SEMANTIC COMMUNICATION CHALLENGES

- Lack of a fundamental theory --> semantic entropy, semantic channel capacity, etc.
- What is a metric for quality comm (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???

MM/HTC/XR Quality Assessment: Open Issues

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

- **QoE for MM/HTC/XR streaming, which may be affected by multiple factors such as:**
  - **Media quality (e.g., evaluated by PSNR)**
  - **Resolution**
  - **Frame rate**
  - **Characteristics of the human visual system (HVS)**
  - **Start-up latency**
  - **Amount of quality level switches and stalls during playback**
  - **Type of user device**
  - **Usability**
  - **Cost of service**
  - **User demographics**

Human Perception

- What is the ultimate objective of Mulsemedia/HTC/XR communication?
- How can we evaluate the quality of Mulsemedia/HTC/XR communication?
- QoE measures the degree of delight or annoyance of users
  - Mulsemedia communication must achieve a high QoE; at least higher than multimedia communication
  - Necessary to study human perception to find out what the most effective/significant senses are
  - Human response to different senses can be very different
  - ML can be used to learn the best QoE model from user experience data

BONUS CHALLENGES

- Development of Efficient HTC/XR/MM encoding and decoding techniques
- QoE-aware design and AI-empowered wireless sensing & motion prediction at the source & destination
- Precise Intra and Inter MM Synchronization
- Design of HTC/MM sensors and actuators
- Study XR/HTC/MM mulsemedia end-to-end latency and data rate 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 control, NW prediction, adaptive control, management