MARINE COMMUNICATIONS:
CHALLENGES & PERSPECTIVES IN THE NEXT DECADE

I.F. AKYILDIZ

Technology Innovation Institute (TII)
Abu Dhabi, UAE
Ian.Akyildiz@tii.ae
http://www.tii.ae

WHY MARINE COMMUNICATION ?

- Traditional approach for ocean-bottom or ocean column monitoring:

- Deploy UW instruments to record data during monitoring mission and then recover them after several months and evaluate the collected data!

Problems:
- No real-time monitoring
- No on-line system configuration (no tuning or reconfiguring the instruments)
- No failure detection
- Limited storage capacity

→DEPLOY MARINE COMMUNICATION NETWORKS TO ENABLE REAL-TIME MONITORING, REMOTE CONFIGURATION, and INTERACTIONS WITH ON-SHORE HUMAN OPERATORS!

Use Cases

- **Ocean Sampling Networks**
  (e.g., Monterey Bay field experiment; Odyssey-class AUVs)

- **Pollution Monitoring and other environmental monitoring** (chemical, biological)
  (Monitoring of ocean currents and winds, detecting climate change, understanding human activities on marine ecosystems, tracking fish or micro-organisms)

- **Disaster Preventions,** e.g., Tsunamis, Seaquakes, Hurricanes

- **Assisted Navigation**
  Locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks

- **Distributed Tactical Surveillance**
  Monitor areas for surveillance, reconnaissance, targeting and intrusion detection

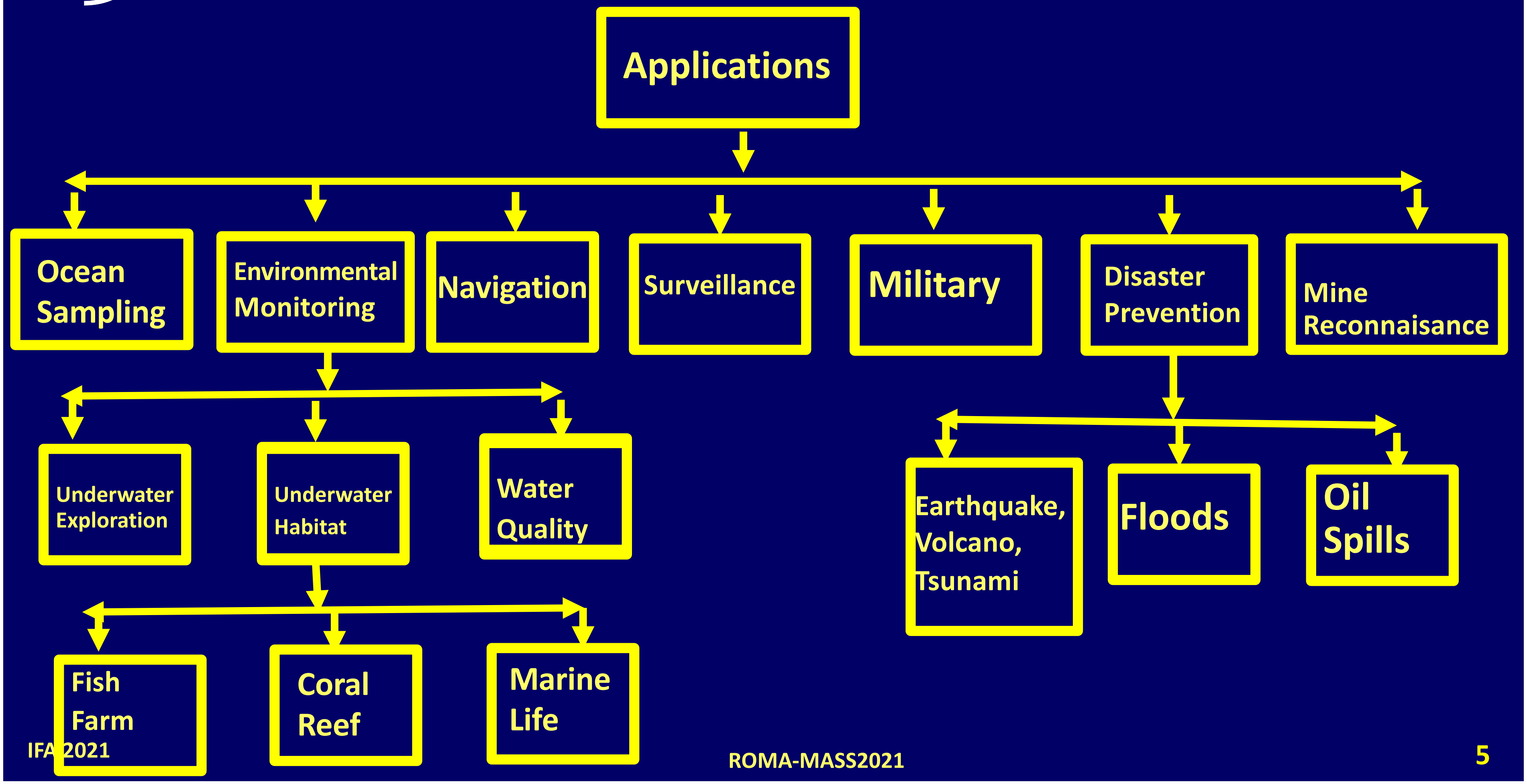
- **Mine Reconnaissance**

MORE USE CASES

- ROV (Remotely Operated Vehicles) Tracking and Navigation
- AUV/UUV Tracking And Communication
- Diver Navigation And Tracking

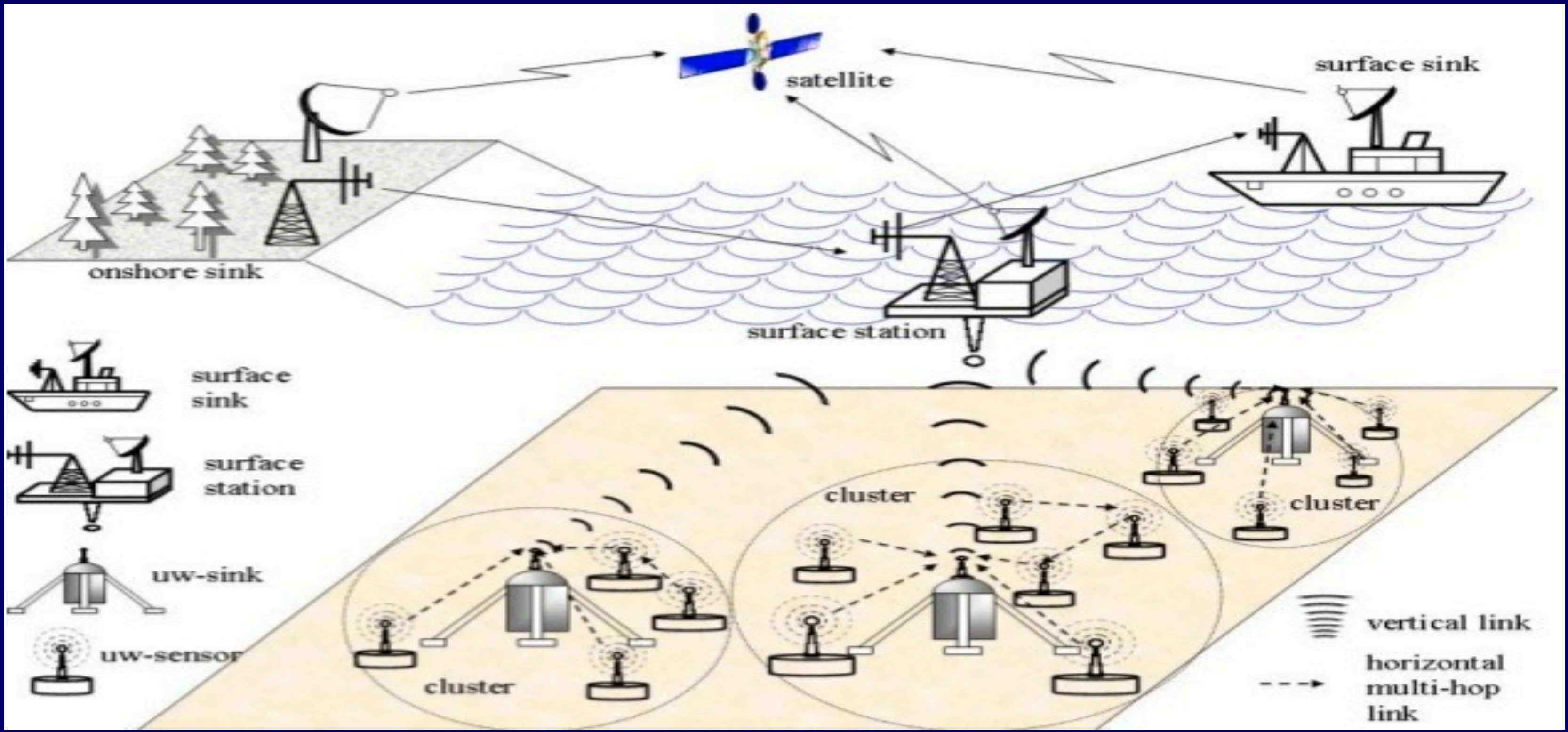
AUV: Autonomous Underwater Vehicles (robots); UUV: Unmanned Underwater Vehicles/Underwater Drones

OVERVIEW


Applications
Ocean Sampling
Environmental Monitoring
Navigation
Surveillance
Military
Disaster Prevention
Mine Reconnaisance
Underwater Exploration
Underwater Habitat
Water Quality
Earthquake, Volcano, Tsunami
Floods
Oil Spills
Fish Farm
Coral Reef
Marine Life

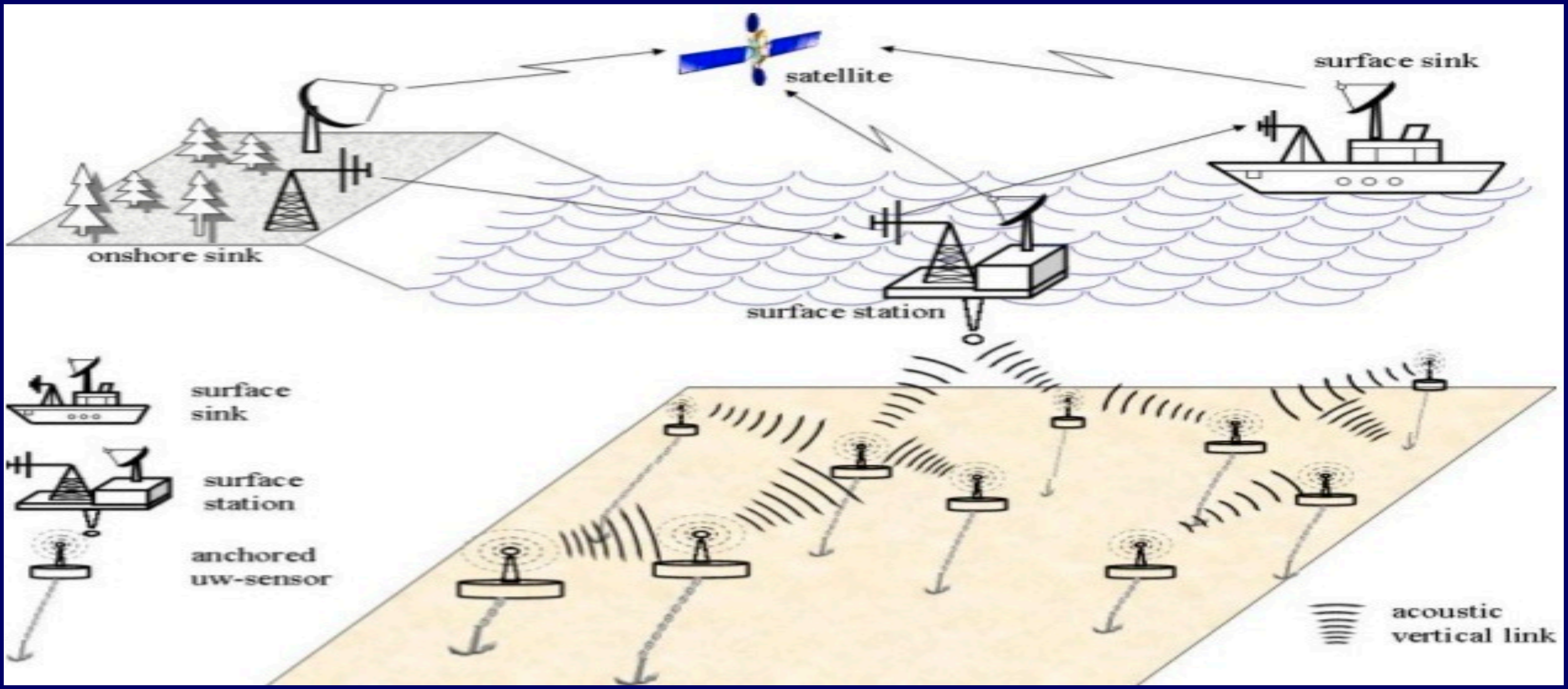
2D ARCHITECTURE FOR OCEAN BOTTOM MONITORING

FOR ENVIRONMENTAL MONITORING OR MONITORING OF UW PLATES IN TECTONICS

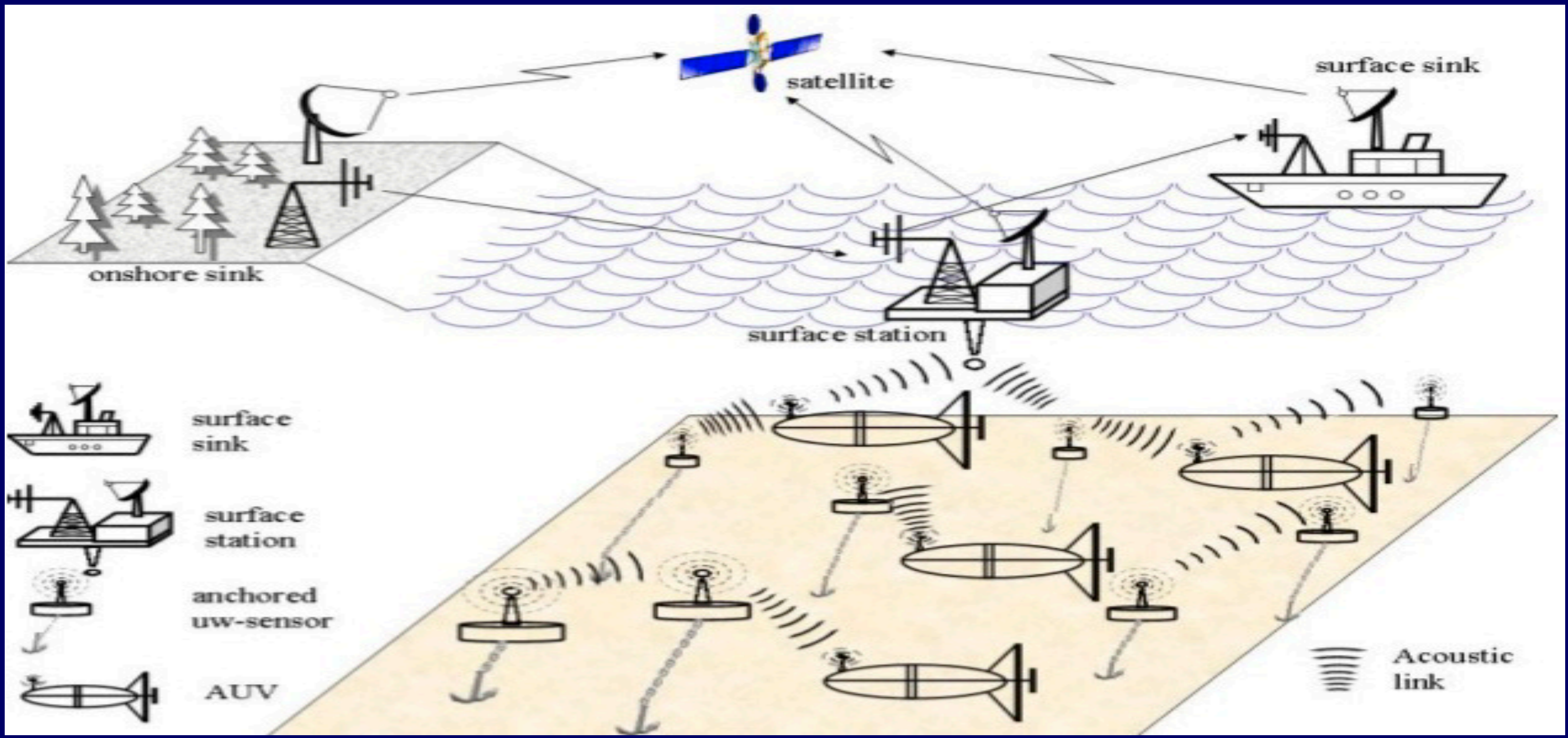


3D STATIC ARCHITECTURE FOR OCEAN COLUMN MONITORING

FOR SURVEILLANCE APPLICATIONS OR MONITORING OF OCEAN PHENOMENA (OCEAN BIO-GEO-CHEMICAL PROCESSES, WATER STREAMS, POLLUTION)



3D DYNAMIC ARCHITECTURE USING AUVS



3D DYNAMIC Architecture using AUVs

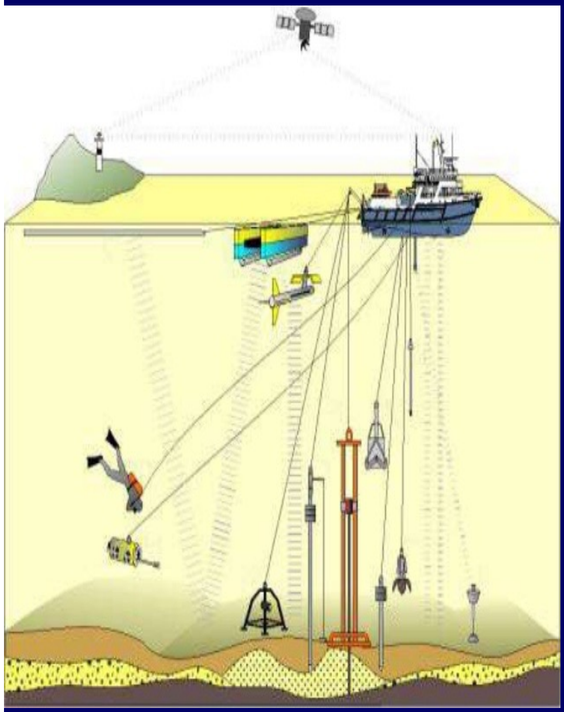
* Inexpensive AUV submarines equipped with multiple UW sensors that can reach any depth in the ocean; e.g., Odyssey class AUVs

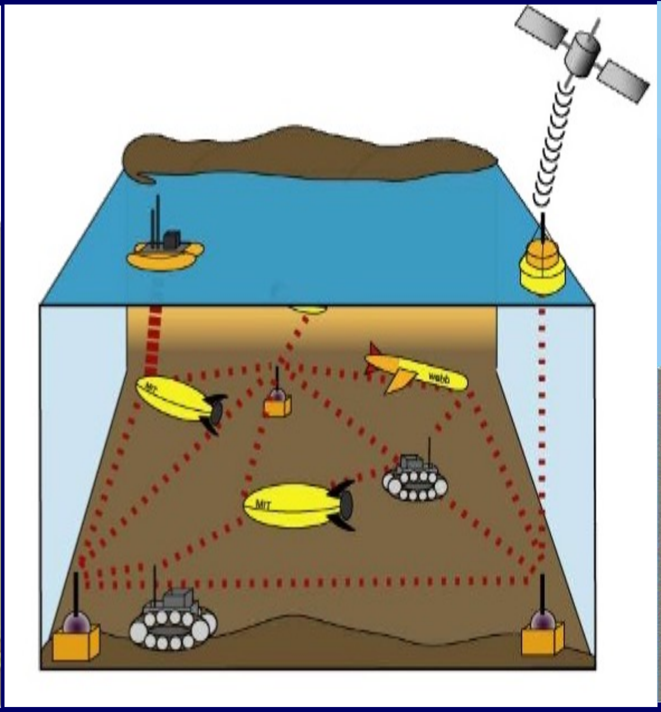
* Drifters

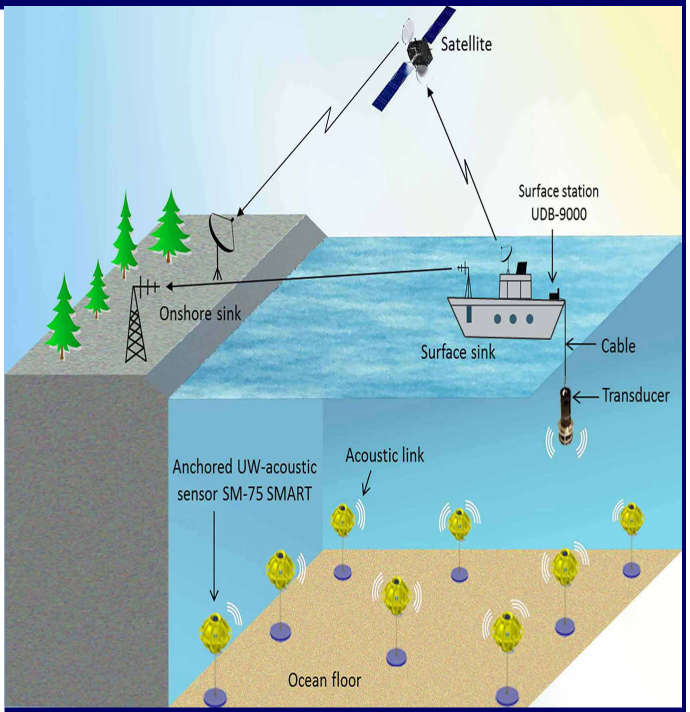
  Use local currents to move and take measurements at preset depths

* Gliders
  - Battery powered and move 25cm/s (0.5 knots)
  - On the surface they can be detected by GPS
  - Onshore operators can interact with Gliders
  - Depth 200m-1500m with lifespans (few weeks to several months)

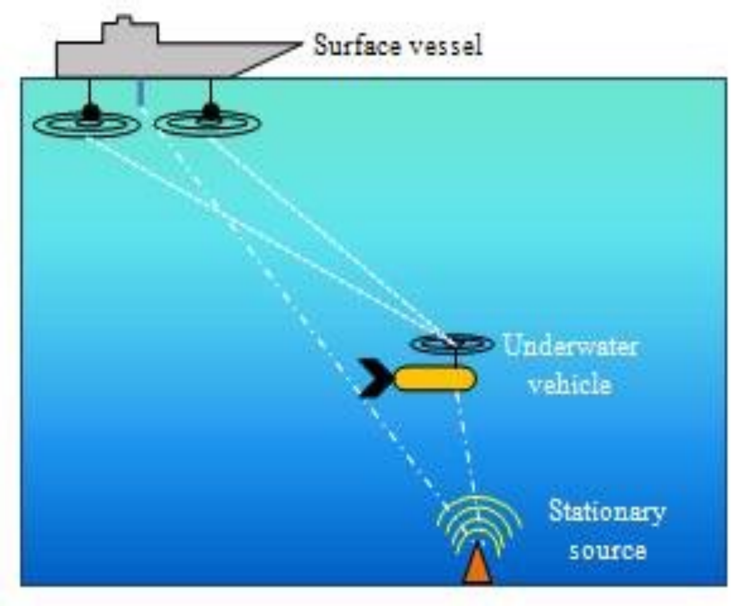
ALTERNATIVE ARCHITECTURES

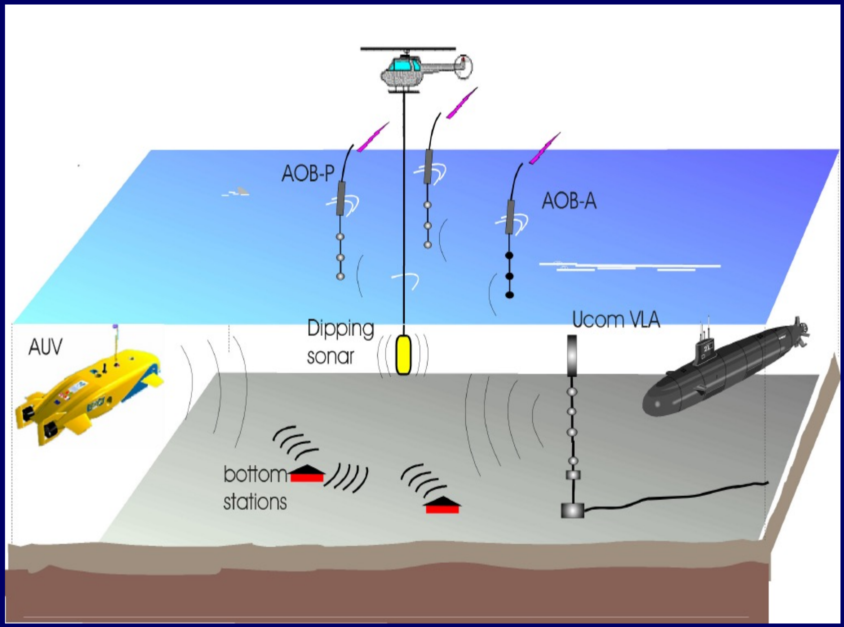






ALTERNATIVE ARCHITECTURES





Ocean Sampling Sensors

http://www.link-quest.com

(Acoustic Transponders)

SoundLink Underwater Acoustic Modems

(High Speed, Power Efficient, Highly Robust)

Designed to combat the 3 main obstacles in UW communication:

Poor Reliability, Low Data Rate and High Power Consumption.

BUOYs

Point measurements in upper water column 10 and 25 mi off Moss Landing

http://www.mbari.org

Monterey Bay Aquarium Research Institute

Drift buoy: Path followed by surface currents

http://www.mbari.org

Surface Station

http://www.link-quest.com

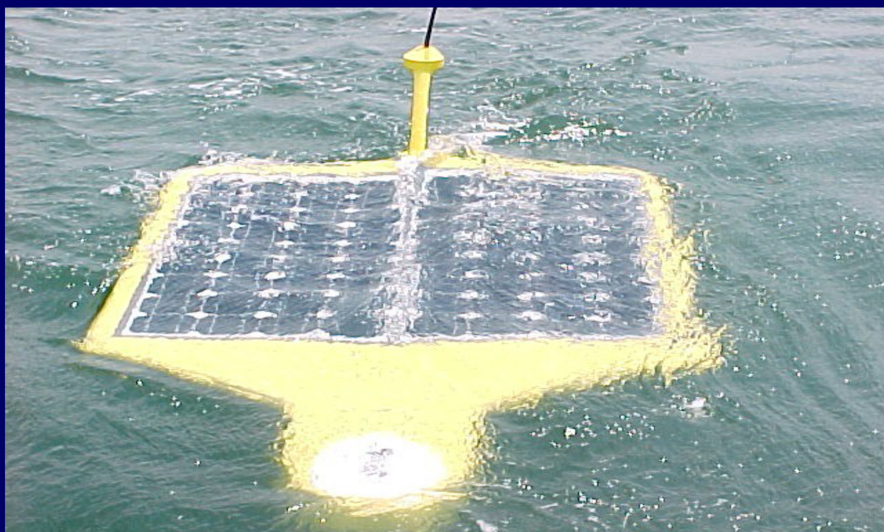
Autonomuos Underwater Vehicles (AUVs)

CARIBOU by **Bluefin Robotics Corporation**

Equipped with state-of-the-art sensors (side-scan sonar and sub-bottom profiler), and can collect high-quality data for:

- **Archaeological remote sensing**
- **Multi-static acoustic modeling**
- **Fisheries resource studies and**
- **Development of concurrent mapping and localization techniques.**

Autonomuos Underwater Vehicles (AUVs)



Solar recharged AUV

http://www.mbari.org/aosn

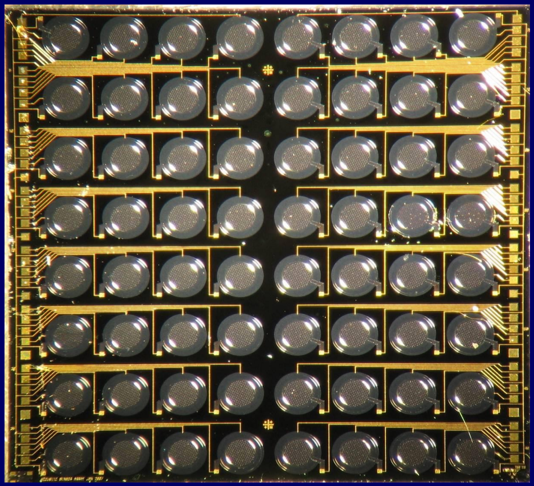
Phantom HD2 ROV

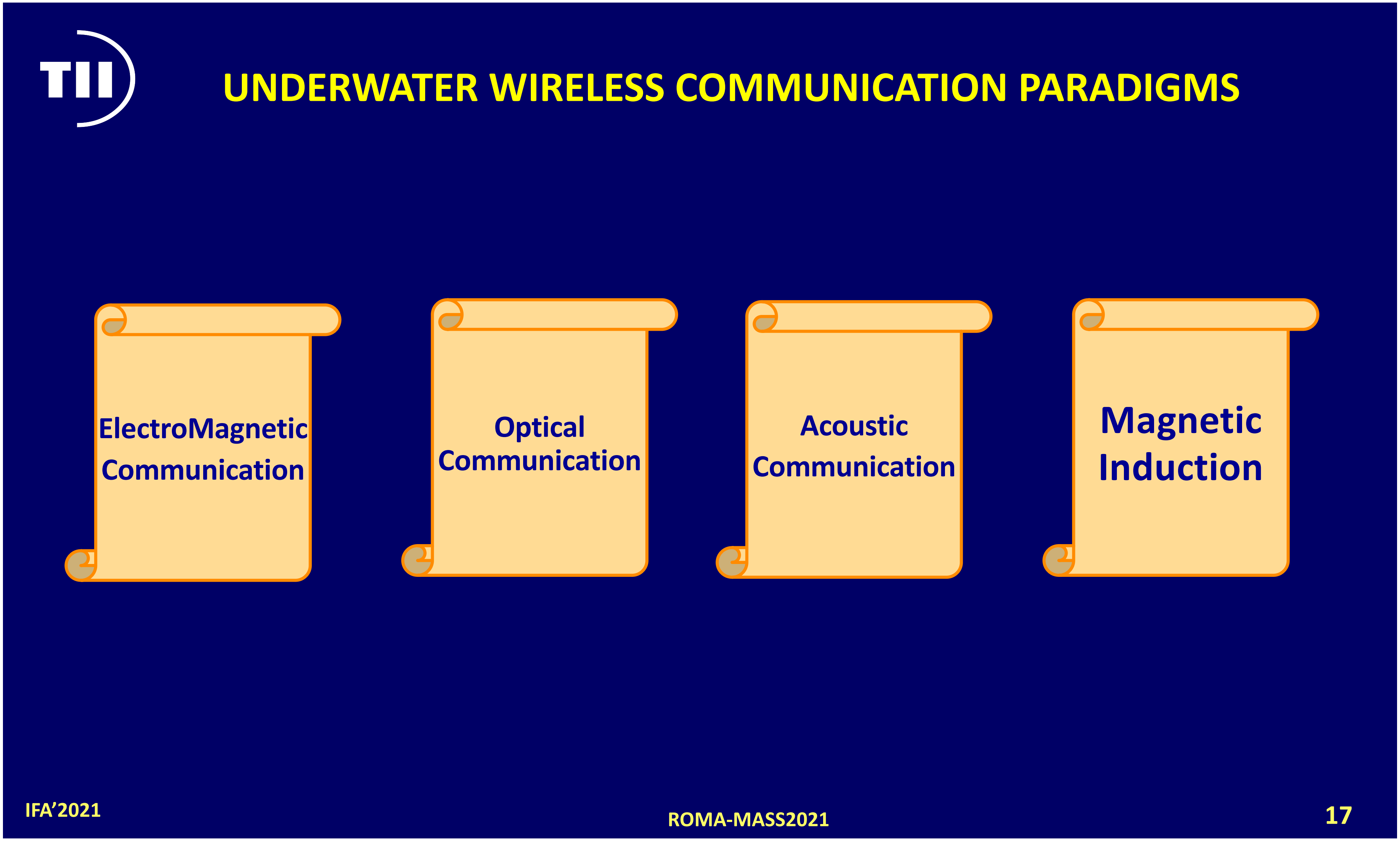
http://www.link-quest.com

How to Generate Acoustic Waves?

Acoustic Transducers

- Piezoelectric (mostly ceramics)
- MEMS (MicroElectroMechanical Systems)




UNDERWATER WIRELESS COMMUNICATION PARADIGMS
ElectroMagnetic Communication
Optical Communication
Acoustic Communication
Magnetic Induction
IFA'2021
ROMA-MASS2021
17

UNDERWATER WIRELESS COMMUNICATION PARADIGMS: RADIO WAVES

* Propagation through conductive sea water only at 30-300Hz frequencies
* Longer distances and relatively high data rates
* High attenuation limiting the communication range
* Large antennae and high transmission power for longer ranges
  For example, the antenna size of an EM transmitter isa couple of meters for a 50 MHz operating frequency.

UNDERWATER WIRELESS COMMUNICATION PARADIGMS: OPTICAL WAVES

* No high such attenuation but high scattering problem
  → Intersymbol Interference (ISI) and short transmission ranges

* High precision in pointing the narrow laser beams at the receiver

* Higher data rates and short distance communications

* Expensive technology

- The most used one both in military and civilian UW com systems
- Long communication ranges
- High Propagation Delays
- Unreliable and unpredictable channel behavior
- Low data rates by complex multi-path fading, prevalent Doppler effects, and significant variation of these properties due to temperature, salinity, or pressure

Magnetic Induction

- Negligible Signal Propagation delays
- Predictable and constant channel response
- Sufficiently large communication range with high data rate
- Stealth Underwater Operations

Comparison of MI, EM, Acoustic, and Optical Underwater Communications

Communication paradigm	Propagation speed	Data rates	Communication ranges	Channel dependency	Stealth operation
MI	3.33×10^7 m/s	~ Mb/s	10–100 m	Conductivity	Yes
EM	3.33×10^7 m/s	~ Mb/s	≤ 10 m	Conductivity, multipath	Yes
Acoustic	1500 m/s	~ kb/s	~ km	Multipath, Doppler, temperature, pressure, salinity, environmental sound noise	Audible
Optical	3.33×10^7 m/s	~ Mb/s	10–100 m	Light scattering, line of sight communication, ambient light noise	Visible

GRAND CHALLENGES AND FUTURE DIRECTIONS

- MAJOR GRAND-CHALLENGE 1: ACOUSTIC COMMUNICATION
  - SOLUTION 1: ULTRA MASSIVE MIMO
  - SOLUTION 2: RECONFIGURABLE INTELLIGENT SURFACES

- CHALLENGE 2: MAGNETIC INDUCTION
- CHALLENGE 3: DESIGN OF CubeUWats (Cube Underwater Systems)
- CHALLENGE 4: SDN/NFV BASED ARCHITECTURES COMPATIBLE WITH 5G/6G
- CHALLENGE 5: UNDERWATER OPTICAL WIRELESS COMMUNICATION
- CHALLENGE 6: UNDERWATER QUANTUM COMMUNICATIONS
- CHALLENGE 7: ENERGY HARVESTING IN UNDERWATER SYSTEMS

CHALLENGE 1: Acoustic Communication Challenges

- **Available bandwidth is severely limited → very low data rates**
- **UW channel is severely impaired (in particular due to multi-path and fading) and Doppler Spread**
- **Very long (5 orders of magnitude higher than in RF terrestrial channels) and extremely variable propagation delays (RRT estimation is complicated)**
- **Very high bit error rates and temporary losses of connectivity (SHADOW ZONES)**

Factors Influencing Acoustic Communications

- **High Delay and Delay Variance**
  - **Propagation speed in the UW-A channel is five orders of magnitude lower than in the radio channel (0.67 s/km)**
  - **Very difficult to estimate the RTT.**

- **Doppler Spread → Can be significant in UW-A and causes ISI**

Challenges of Acoustic Channel

- **Slow Propagation of sound waves in water**
  - 1500m/s versus $3*10^8$m/s in RF
  - Reduce the network throughput considerably

- **Propagation Delay Variance**
  - Prevents accurate estimation of the round trip time

Transmission Path Loss (Acoustic Communication)

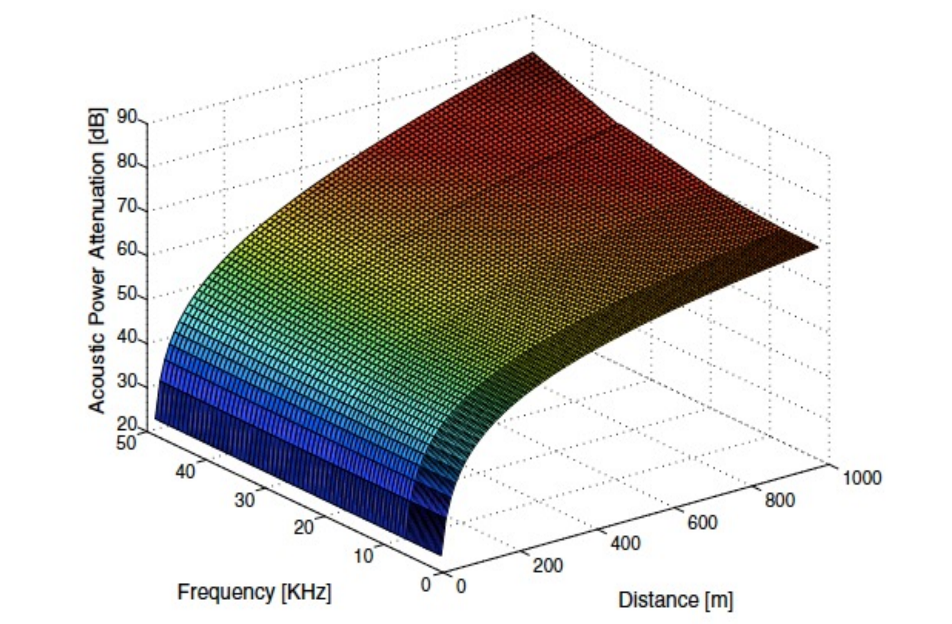
Deep Water → 20
(spherical
spreading)
Shallow water → 10
(cylindrical
spreading)

$$TL(d,f) = 20.\log(d) + \underbrace{\alpha(f)\, d}_{\text{Attenuation due to absorption}} + \underbrace{A}_{\text{Attenuation due to multipath}} \text{ [dB]}$$

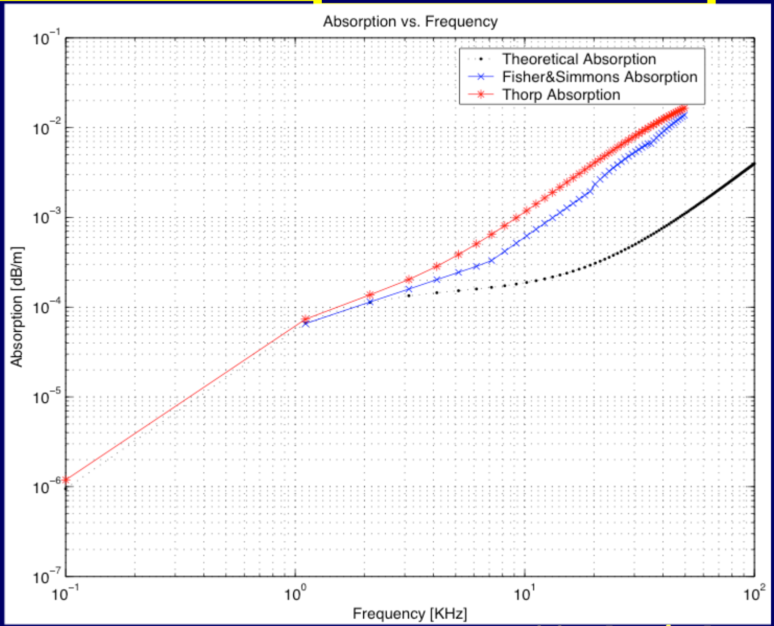
Attenuation due to geometric spreading

Distance dependent attenuation

A=5-10dB
Higher for shallow water due to high multipath



TL increases with increasing freq. & distance



Medium absorption coefficient a(f) [db/m]
as a function of freq. f

GRAND CHALLENGES FOR ACOUSTIC COMMUNICATION

PLETHORA OF (PY, MAC, ROUTING PROTOCOLS) SOLUTIONS published and still the following problems exist:

* Data rates are very low (~kbps – low Mbps)

* Low throughput

* Very long and variable propagation delays*

* Very long end to end delays

SEMI-GRAND CHALLENGES

* Lack of accurate & realistic acoustic channel models
  (accepted by the community and validated by field experiments)

* Protocols standardization and adoption by all modem/device manufacturers

* Reduction of equipment costs (still expensive technology)

* No commercial platforms exist to conduct experiments with high data rates and acceptable costs

HOW CAN WE OVERCOME THESE GRAND CHALLENGES ?

- **SOLUTION IDEA 1: ULTRA-MASSIVE MIMO**
- **SOLUTION IDEA 2: RECONFIGURABLE INTELLIGENT SURFACES**

SOLUTION IDEA 1: ULTRA-MASSIVE MIMO

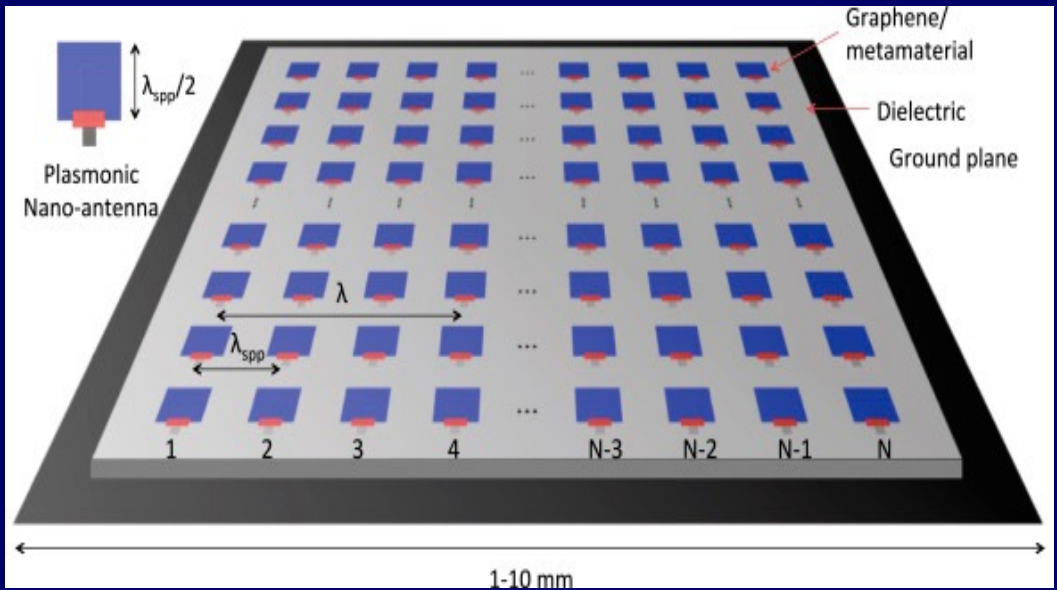
I. F. Akyildiz and J. M. Jornet

"Realizing Ultra-Massive MIMO Communication in the (0.06–10) TeraHertz Band"

Nano Communication Networks, (Elsevier) Journal, Vol. 8, pp. 46-54, March 2016;

U.S. Patent 15/211,503 awarded on Sept. 7, 2017.

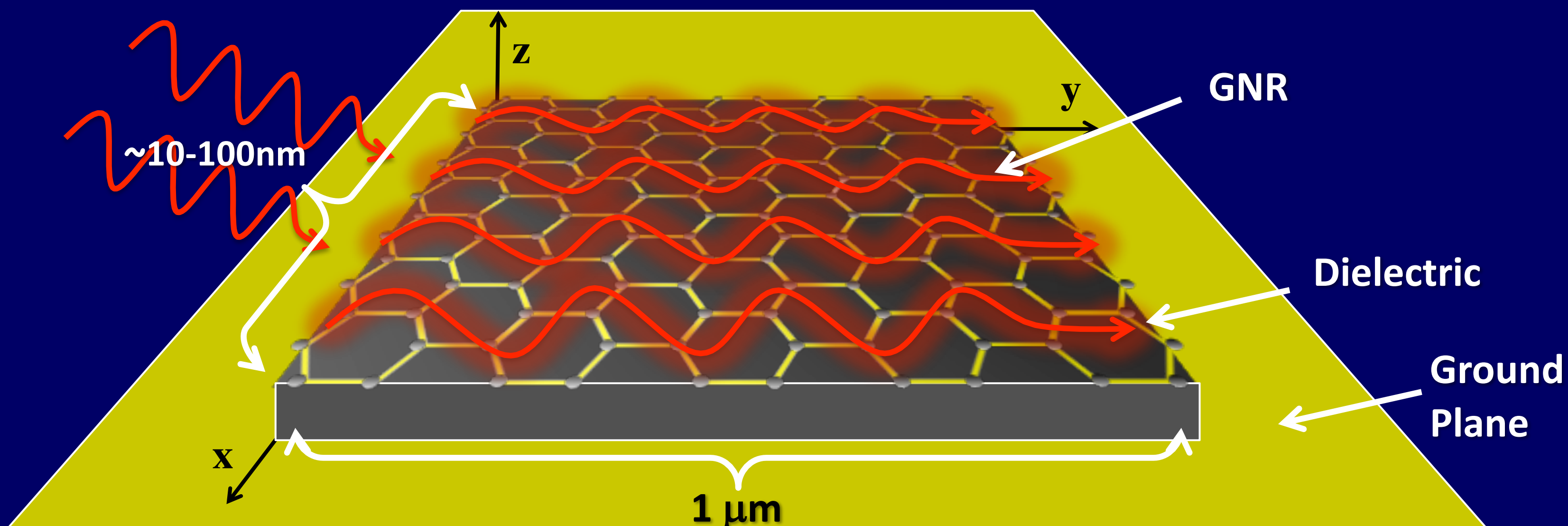
Planar Array with 32x32 antenna elements in total of 1024 elements



Graphene-based Plasmonic Nano-antennas

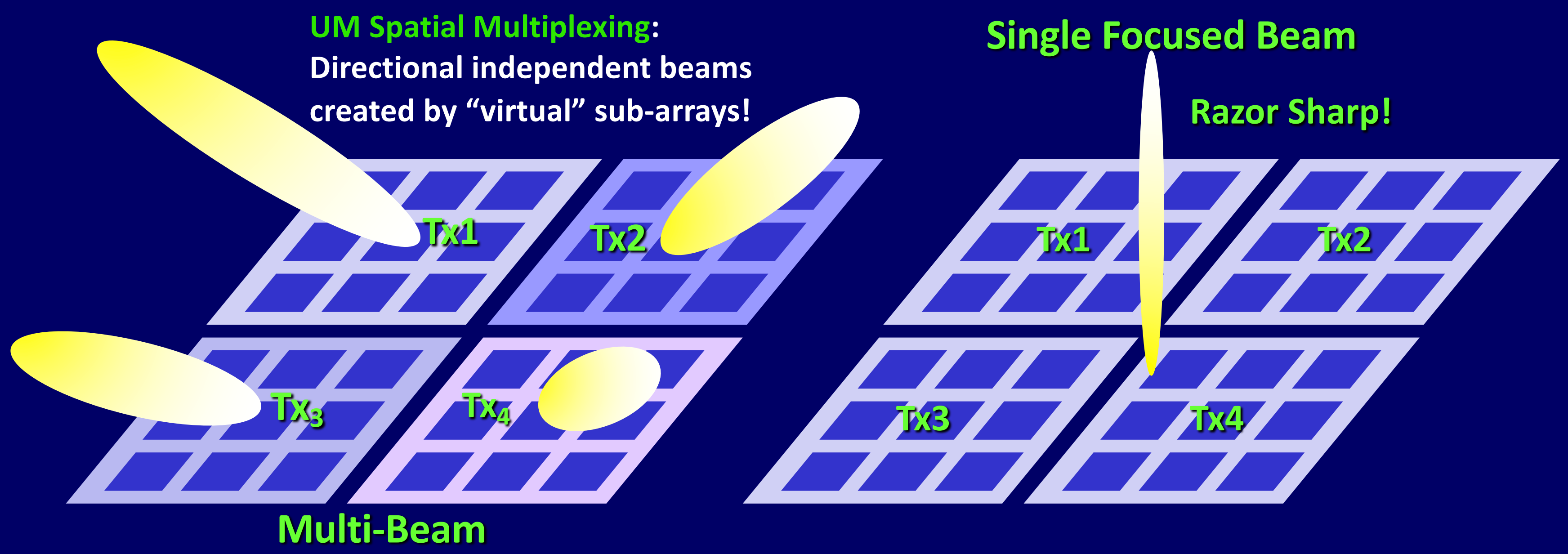
I. F. Akyildiz and J. Jornet
"Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks,"
IEEE Journal of Selected Areas in Communications, Vol. 12, pp. 685-694, Dec. 2013.
Prelim. version in Proc. of 4th European Conference on Antennas and Propagation, 2010
U.S. Patent No. 9,643,841, issued on May 9, 2017.

- Proposed the first nano-antenna based on a GNR Graphene supporting the propagation of Surface Plasmon Polariton (SPP) waves
- Global oscillations of electric charge at the interface between graphene and a dielectric material
- Computed the antenna frequency response and showed that a 1 μm-long antenna can efficiently radiate at 0.1-10 THz frequencies



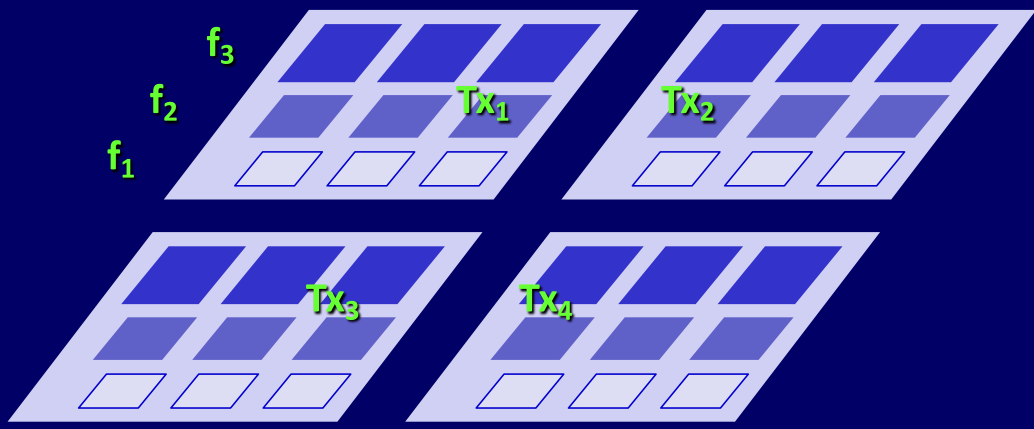
DYNAMIC ULTRA-MASSIVE MIMO FOR INTELLIGENT BEAMFORMING

- By properly feeding the antenna elements, the antenna array can be dynamically switched among different modes
- Also apply ML algorithms for intelligent beamforming



MULTI-BAND ULTRA-MASSIVE MIMO

A nano-antenna array can be designed to communicate over multiple transmission windows simultaneously by electronically tuning the response of fixed-length plasmonic nano-antennas



Open Research Issues for UM MIMO

- Feasibility analysis of large-scale UM MIMO communications over underwater acoustic channels → esp. for lower frequency bands; Use of metamaterials instead of Graphenes.

- Underwater MIMO channel estimation and capacity analysis

- How to accurately estimate channel coefficients for UM-MIMO channel?
  - Antenna spatial correlation & Estimation of thousands of parallel channels

- How to operate the UM antenna arrays to realize the different modes
- Optimal control of each antenna array element, codebook design, beamforming beam steering

IDEA 2: CAN WE USE RECONFIGURABLE INTELLIGENT SURFACES FOR MARINE COMMUNICATION?

BASIC References

- A. Pitsillides, C. Liaskos, A. Tsioliaridou, S. Ioannidis, I. F. Akyildiz,
  "Wireless Communication Paradigm Realizing Programmable Wireless Environments through SW-controlled Metasurfaces"
  US PATENT, 10.547.116 B2; January 28, 2020.

- C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, I. F. Akyildiz,
  "A New Wireless Communication Paradigm through SW-controlled Metasurfaces"
  IEEE Communications Magazine, Sept. 2018.

- C. Liaskos, A. Tsioliaridou, A. Pitsillides, I.F. Akyildiz, N. Kantartzis, A. Lalas, X. Dimitropoulos, S. Ioannidis, M. Kafesaki, and C. Soukoulis,
  "Design and Development of Software Defined Metamaterials for Nanonetworks,"
  IEEE Circuits and Systems Magazine, vol. 15, no. 4, pp. 12-25, 4^{th} Quarter 2015.

Different Nomenclatura

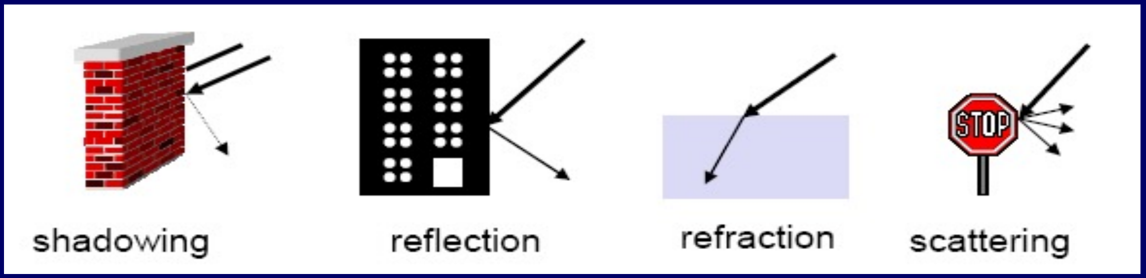
- Intelligent Communication Environments (ICE)
- Intelligent Communication Surfaces (ICF)
- Reconfigurable Intelligent Surfaces (RIS)
- Programmable Wireless Environments (PWE)
- Programmable Metasurfaces
- Hypersurfaces
- Large Intelligent Surfaces (LIS)
- Intelligent Reflecting Surfaces (IRS)
- Smart Radio Environments

……..

WHY RECONFIGURABLE INTELLIGENT SURFACES ?

Waves undergo multiple uncontrollable alterations as they propagate through a wireless environment.

- **Path Loss**
- **Attenuation**



Absorption **Diffraction**

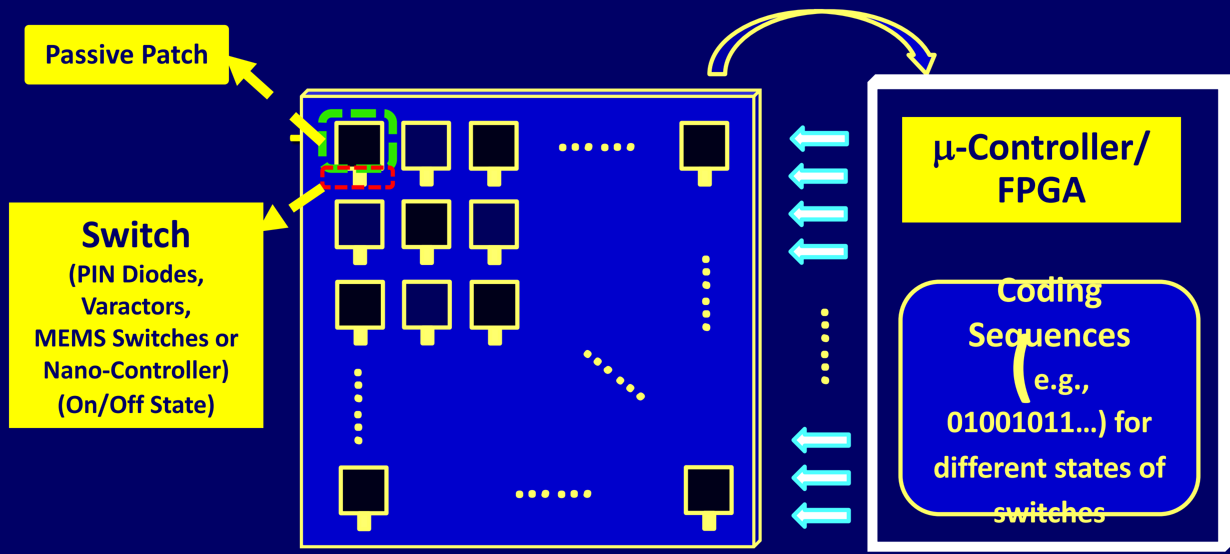
- **Interference**
- **NLOS**
- **Fading**
- **Doppler Effects**

- **Distance esp. for 60GHz and TeraHertz bands**
- **Coverage**
- **Energy Consumption**
- **Security (e.g., Eavesdropping, Jamming, etc.)**

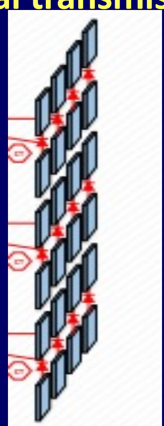
CONVENTIONAL APPROACHES

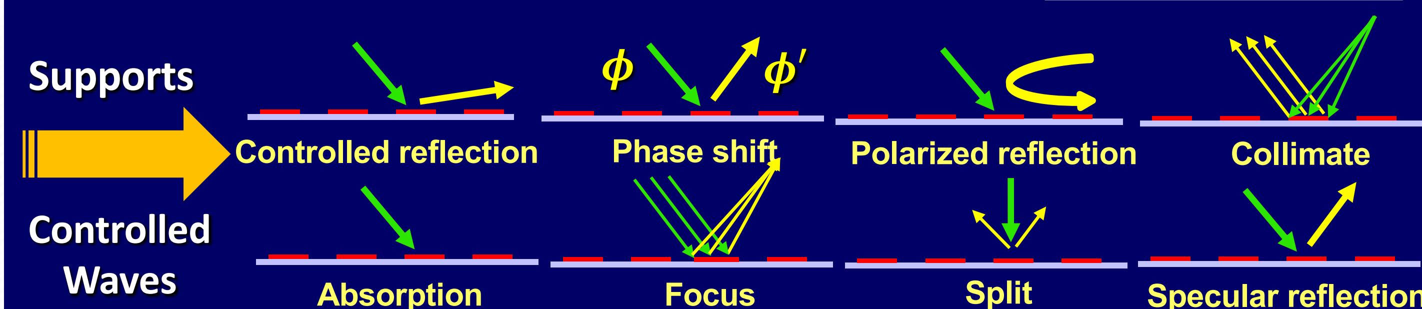
- **PHY Layer solutions, e.g., adaptive antenna, MIMO, beamforming, adaptive modulation, dynamic spectrum allocation, encoding and plethora of MAC and ROUTING protocols**
- **Although successful, they all have separate degrees of efficiency**
- **Also the random channel behavior still greatly affects the performance !!**

RECONFIGURABLE INTELLIGENT SURFACES (RIS)



Intelligent Com Environments turn passive (inactive) wireless propagation environments into active participants in wireless signal transmission





ADDITIONAL BENEFITS

Optimization of Beamforming and Spatial Diversity

Spatial, spectral, and temporal allocations of resources for multi-user communications

Maximize data rates under energy constraints

Track mobile users and maintain their connectivity through phase shift optimizations

Optimum and adaptive decisions for QoS

Wireless Power Transfer

Security (Blocking Intruders, Avoiding Eaves Droppers, Jammers)

EU-FET PROJECT VISORSURF

http://www.visorsurf.eu

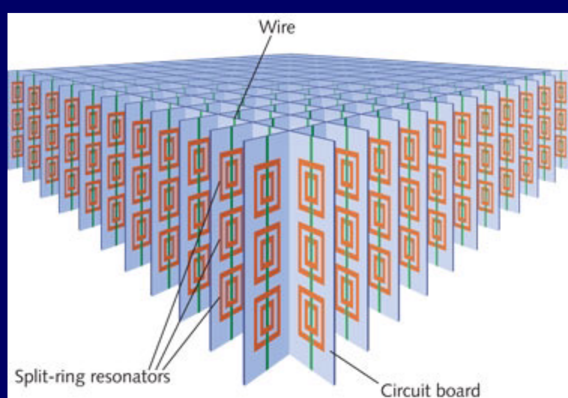
Design, build, and demonstrate software-defined metasurfaces (HyperSurfaces) with end-to-end functionality (TERRESTRIAL!!!)

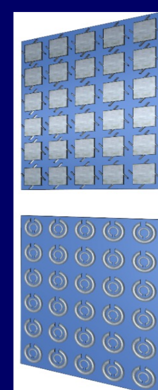
- "A HyperVisor for MetaSurface Functionalities"
  - Controlling & customizing EM propagation with software!

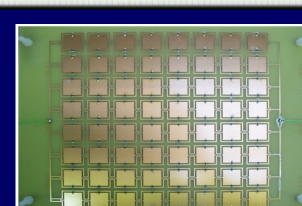
- Start date: 1/1/2017
- Duration: 42 months
- Coordinator: FORTH Crete, Greece
- 7M Euro (2017-2021)

METAMATERIALS for LOWER FREQUENCIES

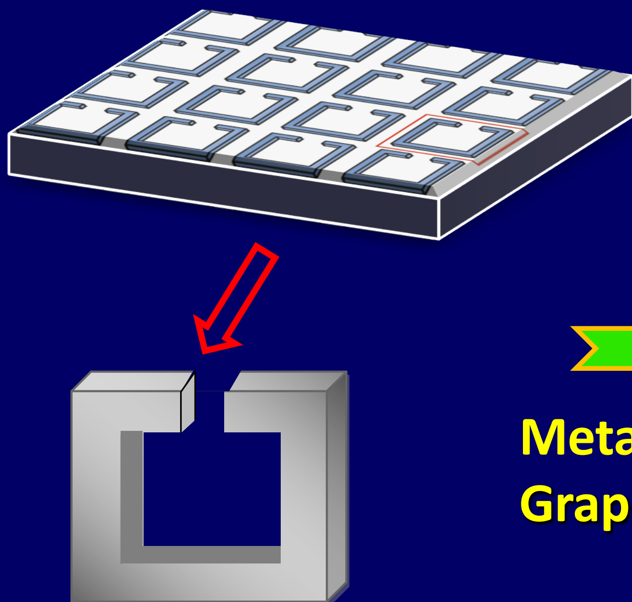
- A metamaterial ("beyond") is a material engineered to have a property that is not found in nature
- Manipulation of EM waves: block, absorb, enhance, or bend waves, to achieve benefits that go beyond what is possible with conventional materials
- Their precise shape, geometry, size, orientation and arrangement gives them their smart properties







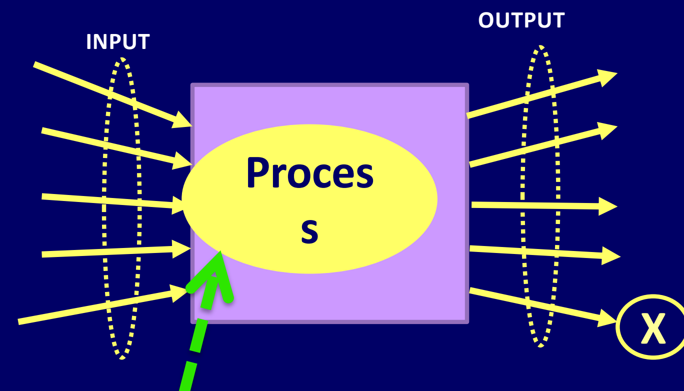
Metamaterial Basics



Schematics of the Elementary Cell

Metasurfaces/
Graphenes

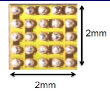
Completely re-engineer incoming EM waves

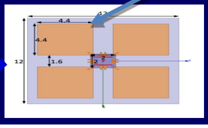


STEER, ABSORB, POLARIZE, SPLIT,
FREQ_FILTER, ALTER_PHASE, FOCUS,
CUSTOM EM/MAG FIELD At output(s)

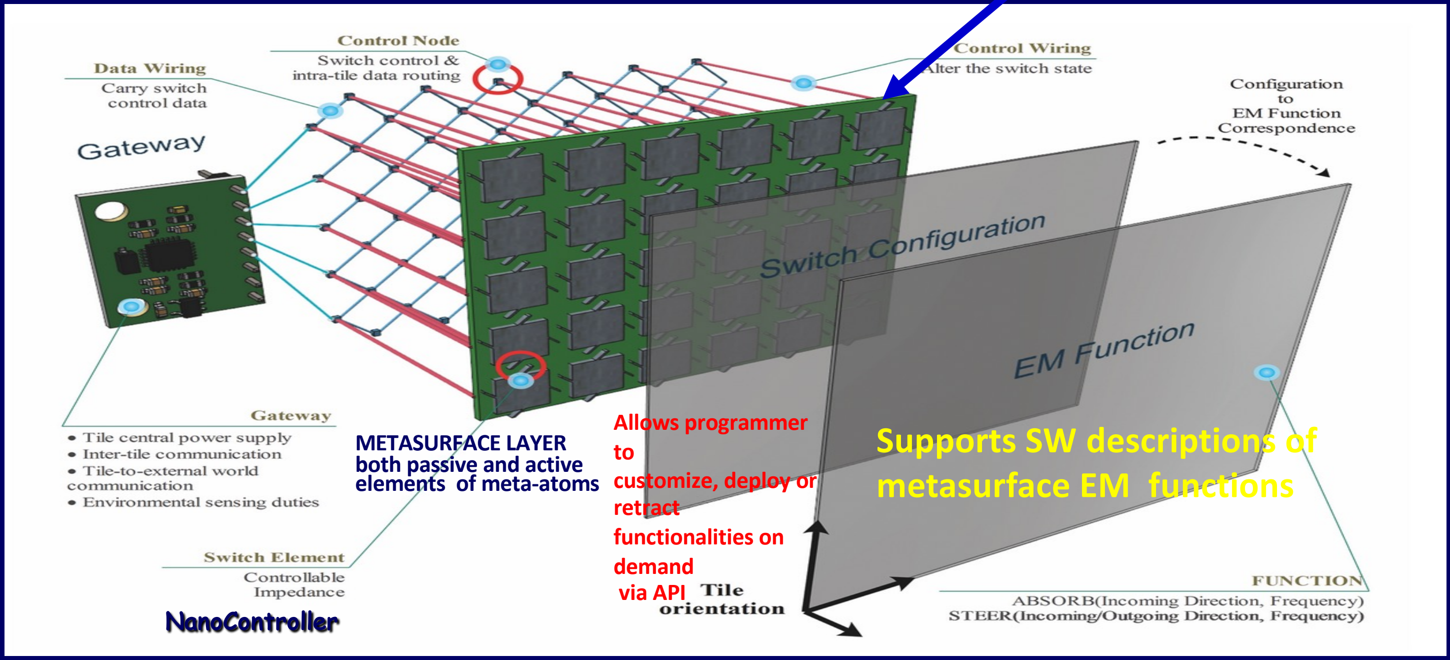
HYPERSURFACES: Programmable (SOFTWARE DEFINED) SURFACES

A. Pitsillides, C. Liaskos, A. Tsioliaridou, S. Ioannidis, I. F. Akyildiz,
"Wireless Communication Paradigm Realizing Programmable Wireless Environments through Software-controlled Metasurfaces"
US PATENT, 10.547.116 B2; January 28, 2020.



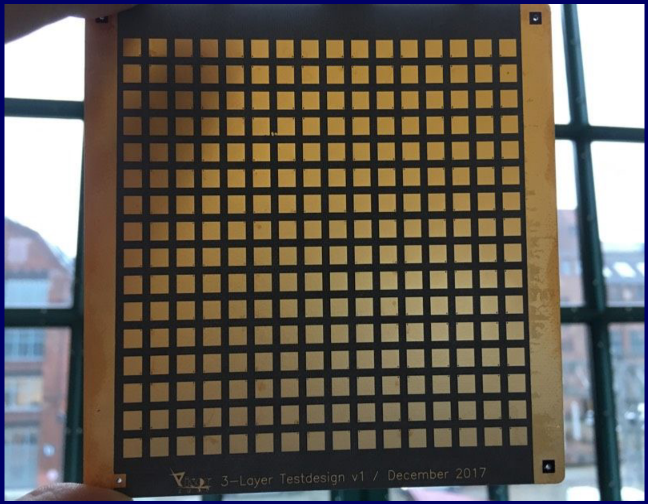


meta atoms/ metallic patches/ unit cells



PROTOTYPING

COURTESY OF FRAUNHOFER INSTITUTE BERLIN

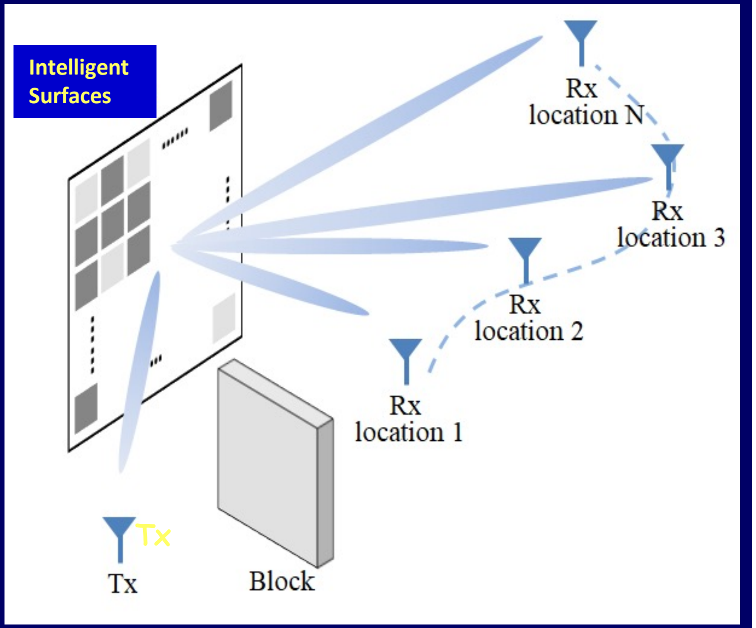


- First prototype is ready for evaluation
  - Software & Hardware
- More prototypes to follow:
  - Exotic ASIC solutions
  - Graphene-based, THz control

- Paving the way for smart, connected materials with programmable physical properties

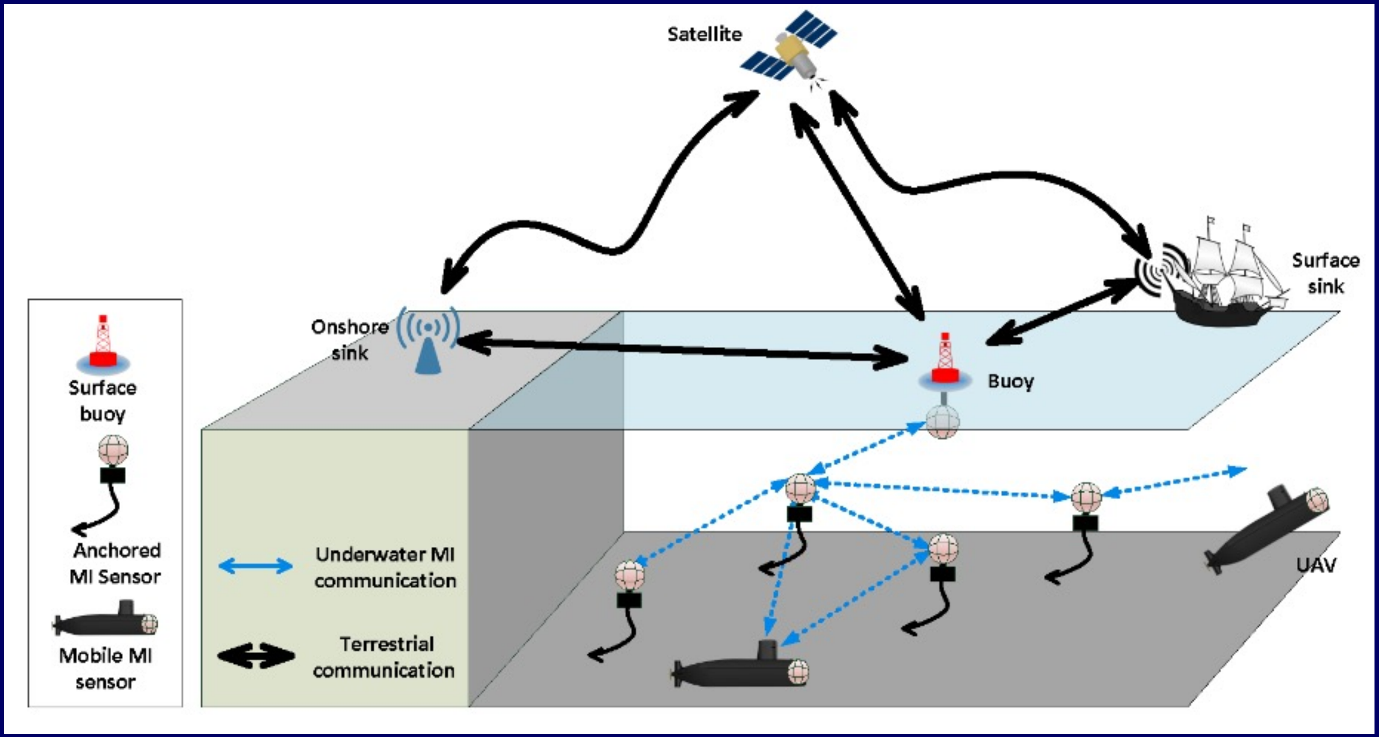
OPEN RESEARCH TOPICS

- How to acquire channel state information in rapid time-varying underwater channel?
- How to detect, track, and localize multiple mobile users/objects/devices in channels?
- Real-time beam tracking scheme for underwater vehicles and random trajectories



CHALLENGE 2: MI-based MARINE Communication

I. F. Akyildiz, P. Wang and Z. Sun,
"Realizing Underwater Communication through Magnetic Induction,"
IEEE Communications Magazine, Nov. 2015.



Advantages of MI-based MARINE Communications

- Negligible propagation delay
- Better delay performance
- No multipath fading
- No scattering
- No Doppler effect
- Low power consumption
- Simple transceiver design

- Predictable and Constant Channel Conditions

  (PHY synchronization will be easy)
- Packet loss rates are constant and predictable
- High Data Rates
- Immune to acoustic and ambient light noises
- Tx range and channel are independent of the water turbidity
- Stealth Underwater Operations
- Cost of MI coils is very low → Scalability

CHANNEL MODELS FOR DIRECTIONAL MI COIL

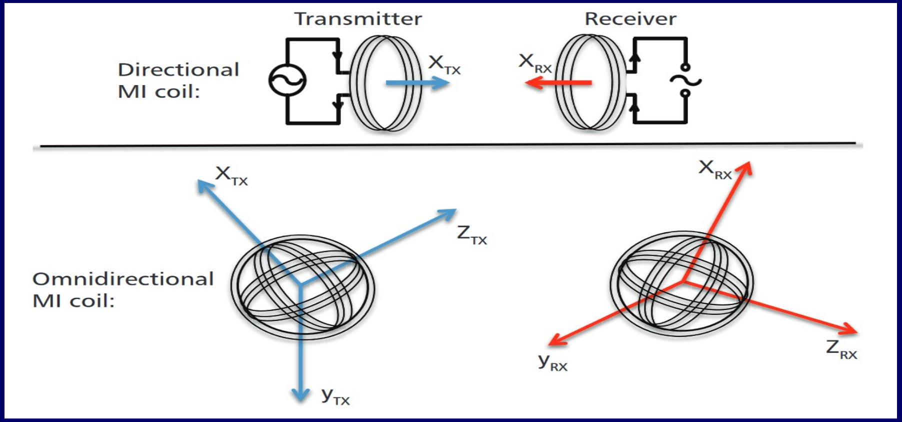
M. C. Domingo,
"Magnetic Induction for Underwater Wireless Communication Networks,"
IEEE Tr. on Antennas and Propagation, pp. 2929 – 2939, 2012.

MI path loss is derived as a function of the

- Operating frequency,
- Transmission distance,
- Coil antenna size,
- # of turns,
- Relative angle between the two coils, and
- UW environmental conditions, especially the water conductivity.

NEW IDEA: 3D COIL ANTENNA

I. F. Akyildiz, P. Wang and Z. Sun,
"Realizing Underwater Communication through Magnetic Induction,"
IEEE Communications Magazine, Nov. 2015.



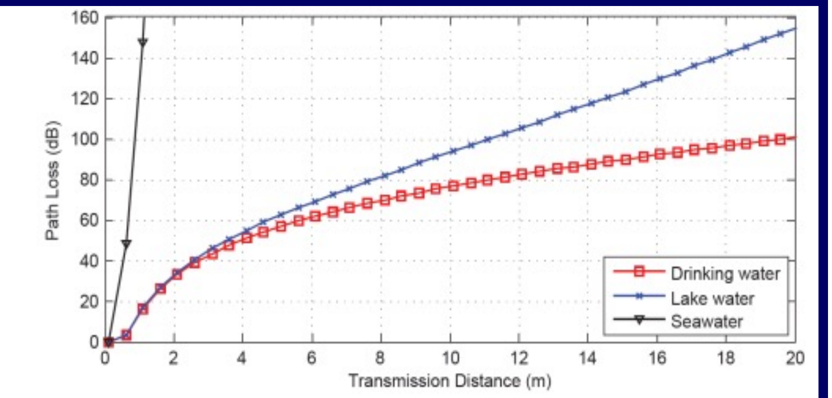
- Data carried by a time varying MI generated by the modulated sinusoid current along an MI coil antenna at the Tx.
- Rx retrieves the information by demodulating the induced current along the receiving coil antenna
  - MI Tx work best at MHz band that has a wavelength of tens of meters.
  - Since the com range in UW MI systems is within one wavelength, even if there exist multiple paths between the Tx, the phase shifting of multiple paths is so small that the coherence BW is much larger than the system BW.
  - Hence, the fading and channel distortion are negligible.

CHANNEL MODELS FOR 3D DIRECTIONAL MI COIL

H. Guo, Z. Sun, and P. Wang,
"Channel modeling of MI UW Communication using Tri-directional Coil Antenna,"
Proc. IEEE Globecom 2015, San Diego, USA, 2015.

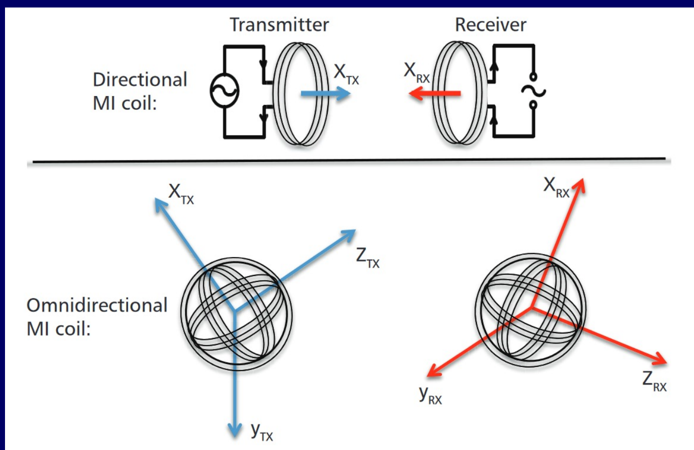
Antenna Config.	Operating Frequency	Operating Environments
10 cm radius 20 turns of AWG26 wire	10 MHz	1. Seawater with conductivity 4 S/m
		2. Lake water with conductivity 0.005 S/m
		3. Drinking water with conductivity 0.0005 S/m

- Small sensor can achieve 30m & 15m range in Case 3 and 2 but less than 1m range in Case 1
- High conductive seawater induces significant Eddy current incurring very high path loss.
- Data rates can reach tens of of Kbytes/sec

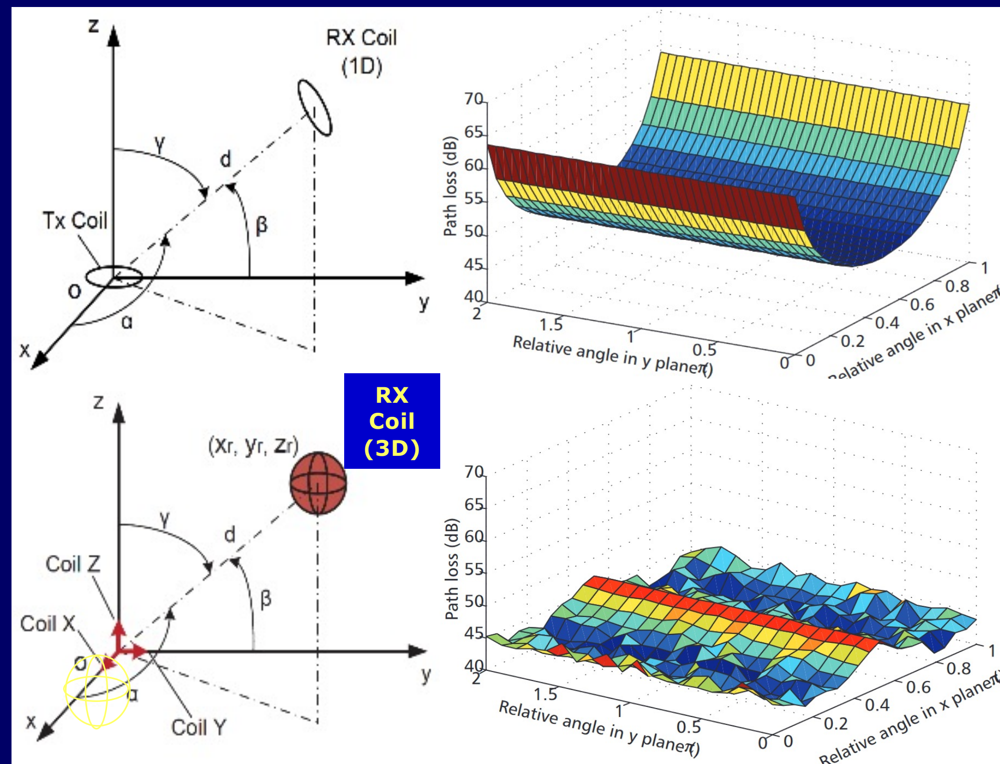


(a) Path loss of MI underwater communications.

PATH LOSS OF UNI- vs 3-DIRECTIONAL RECEIVERS



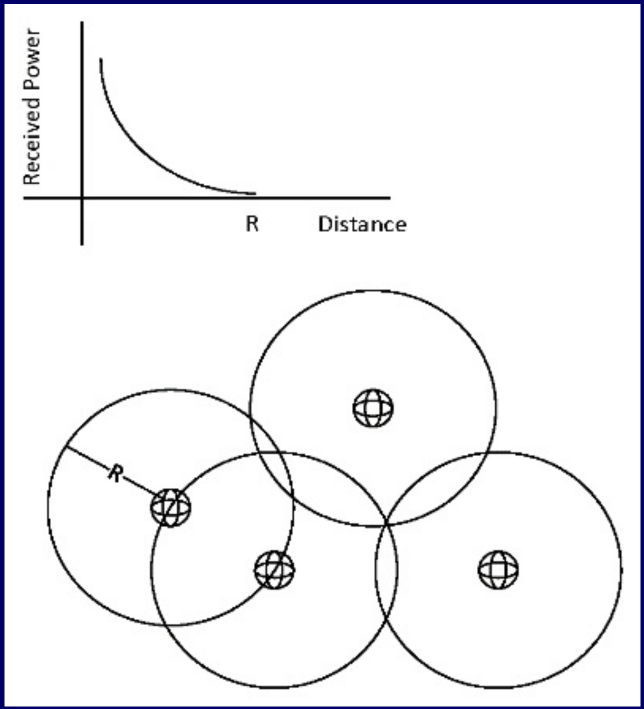
- **MI antenna with 3 orthogonal coils**
  - **Omni-directional communications**
  - **Enhanced received signal strength**
  - **Can be used for 3D localization**



Pathloss independent of relative locations between sensors

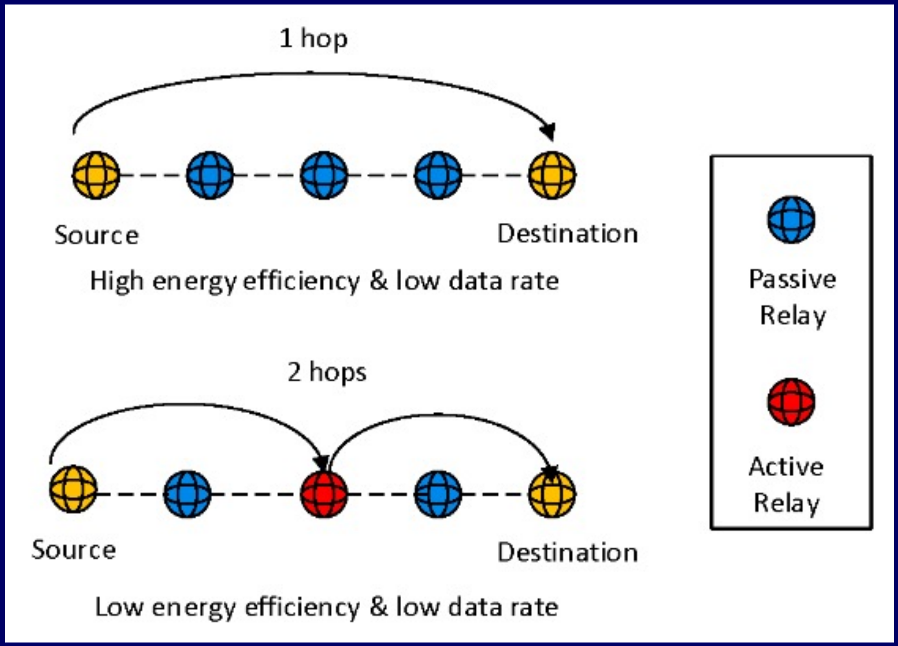
OPEN PROBLEM: MI-based UW MAC

- **Negligible propagation delays**
- **Limited Interference**
  - Received power is negligibly small at certain distance
  - Protocol/disc model sufficient for MAC design without adopting complicated SINR model
- **Objective:**
  - Develop highly-scalable CSMA-type MAC



OPEN PROBLEM: MI-based UW Routing

- **Passive Relay:**
  - Do not consume any energy
  - Act as the MI waveguide
  - Low end-to-end data rate due to low received power at destination
- **Active Relay:**
  - Consume energy for receiving data and forwarding it to next hop
  - High end-to-end data rate due to high received power at destination



- **Objective:**
  - Dynamically select the next-hop node & relay nodes of sensors for optimal tradeoff between energy efficiency and delay

OPEN RESEARCH ISSUES FOR MARINE MI Communication

- 3D MI Channel Modeling
- UW 3D-MI Coil Antenna Design
  (Size, # of turns, as well as the lumped and the distributed impedance)
- Transmission range extension through UW MI waveguide
- UW MI Transceiver Design (self diagnose and self healing)
- Energy Modeling & Energy Harvesting Solutions & Energy Charging
- 3D-MI based Communication Protocols Design
  (higher network throughput, much lower delay and better scalability)
- Advanced PHY solutions to increase BW
- Transport layer protocols for delay-sensitive and delay-insensitive applications
- Robust MI-based network deployment
- AUV/UUV/Rover Deployments with Hybrid (MI, Acoustic, EM) Modes and Fixed/Mobile Communication Modes

CHALLENGE 3: DESIGN of CubeUwats (Cube Underwater Systems)

GRAND CHALLENGE:

- **Implement an UW wireless communication network on-the-fly.**

MOTIVATIONS:

*** High development cost, associated to**

- **HW design and implementation**
- **System integration in UW-proof platform**

*** Lack of standardization, both at**

HW-level: **difficult to integrate components from different manufacturers**

SW-level/Communications: **difficult to achieve inter-operability of networks**

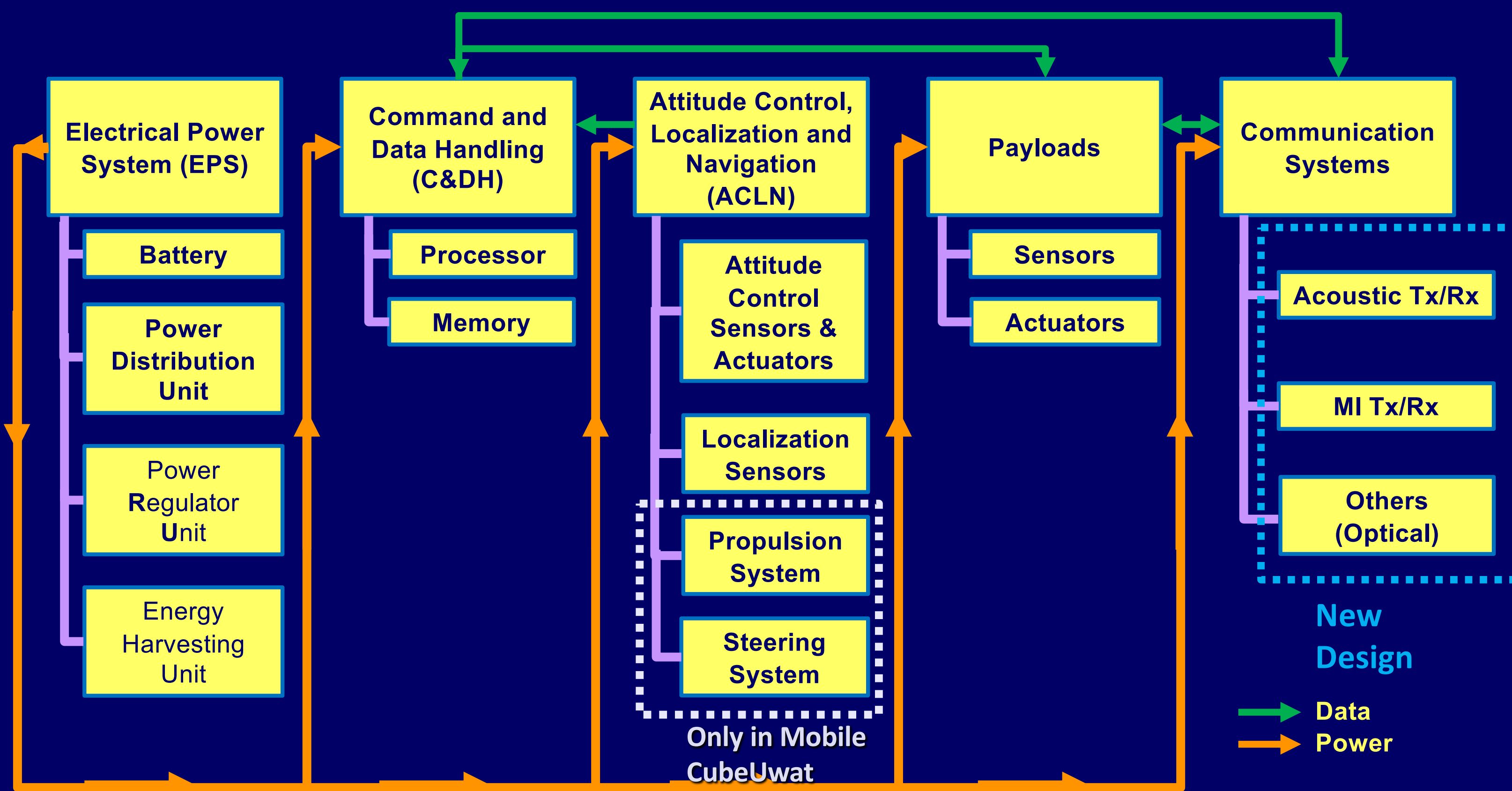
*** Long design and implementation cycle**

CHALLENGE 3: CubeUWats

- Made up of multiple cubes or units:
  - 1 cube = 1 U = 10 cm x 10 cm x 10 cm

- Advantages of CubeUwat
  - Scalable
  - Flexible
  - Low cost
  - Built with commercial off-the-shelf components
  - Able to carry different payloads (sensors/actuators)
  - Short development to deployment period

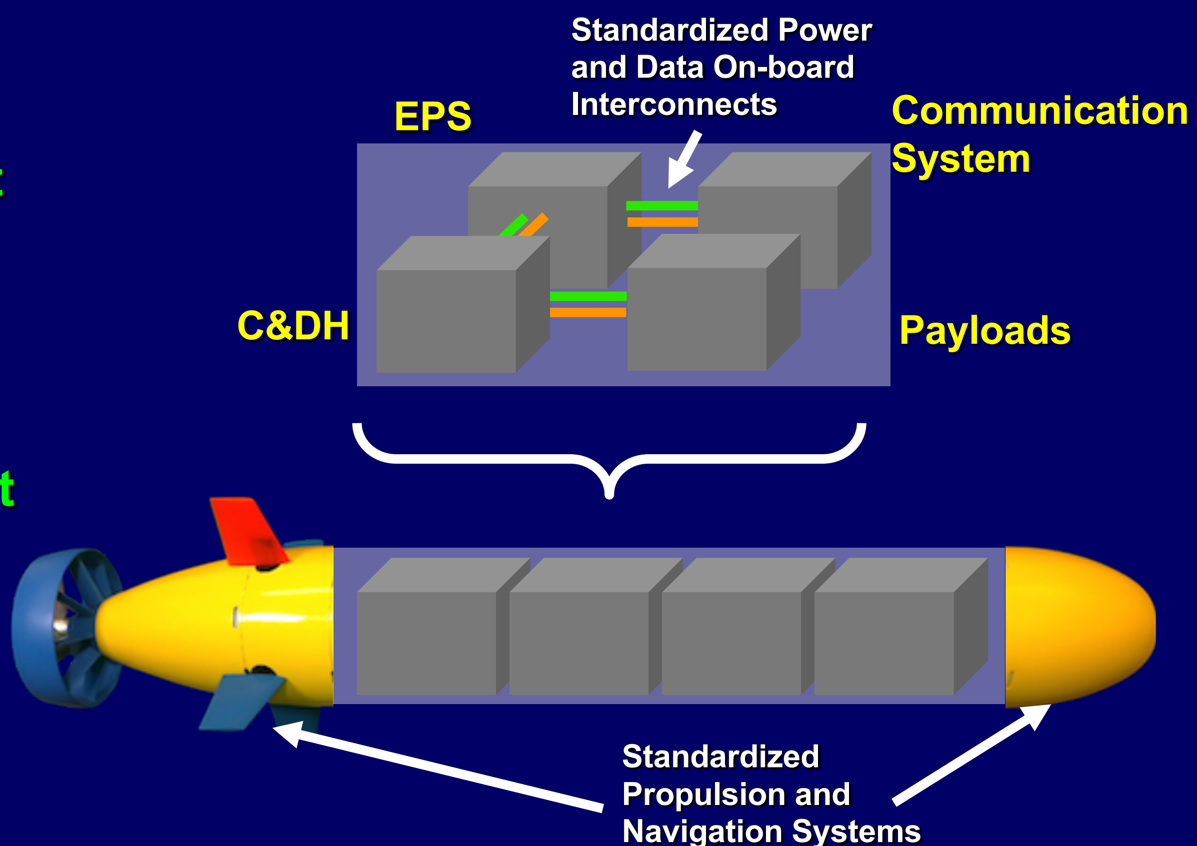
Functional Components in CubeUWat



CubeUWat Modular Designs

Static CubeUwat

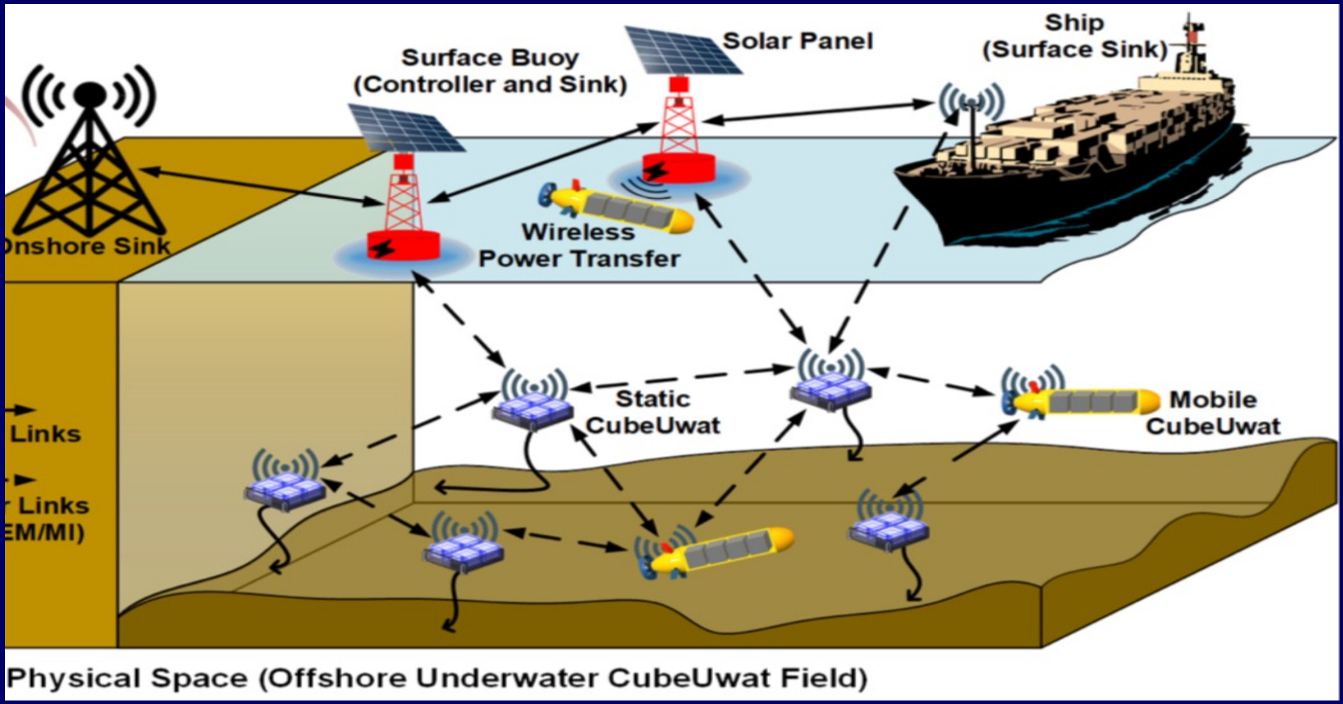
Mobile CubeUwat



CubeUWats Architecture

Decide how to deploy the CubeUwats (maybe not chained)

SDN/NFV based Architecture?



Open Research Issues: CubeUWats Development

- **HW Design:**
  - Development of each functional block (EPS, C&DH, ACLN, …)
  - Determine wireless or wired connection between functional components in CubeUwat

- **SW Development:**
  - Definition of an open-source platform to program CubeUwats
  - Develop communication protocols
  - Determine optimal topology decisions

- Combine the CubeUwats with the SDN/NFV based for Underwater architecture.

All these are on top of all the communication and networking challenges!!!

Open Research Issues: CubeUWat Communication Networks

- Deployment optimization to maximize the area of coverage with min # of CubeUwats
- Adaptive operation modes among EM, MI, and acoustic communications
- Optimal mobile CubeUwat route selection
- Power/Energy transfer to static CubeUwats
- Many many more….

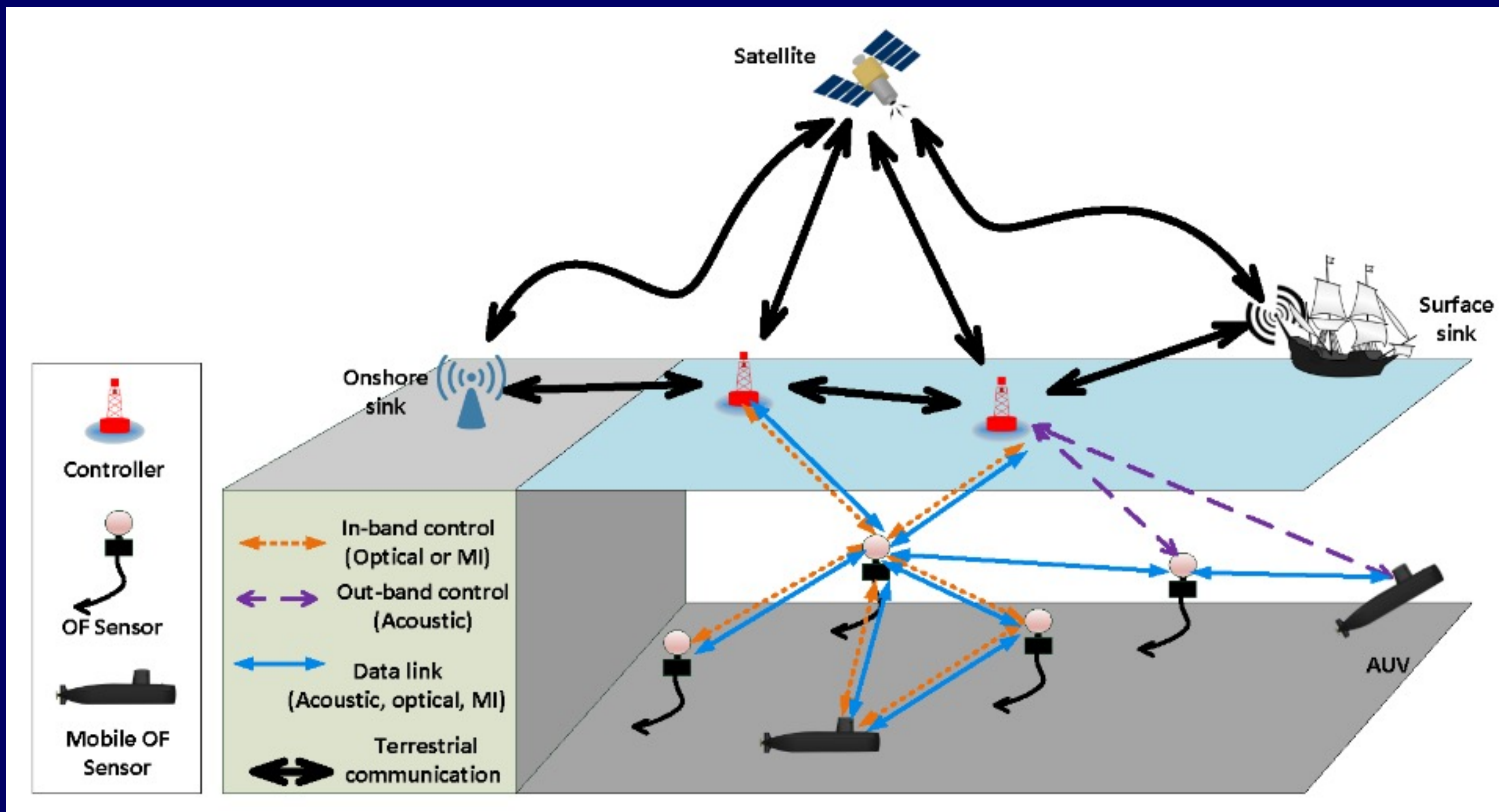
CHALLENGE 4:

Can SDN/NFV be used for Next-Generation Underwater Communication Systems and also support Multimode (EM, Acoustic, MI) Communication?

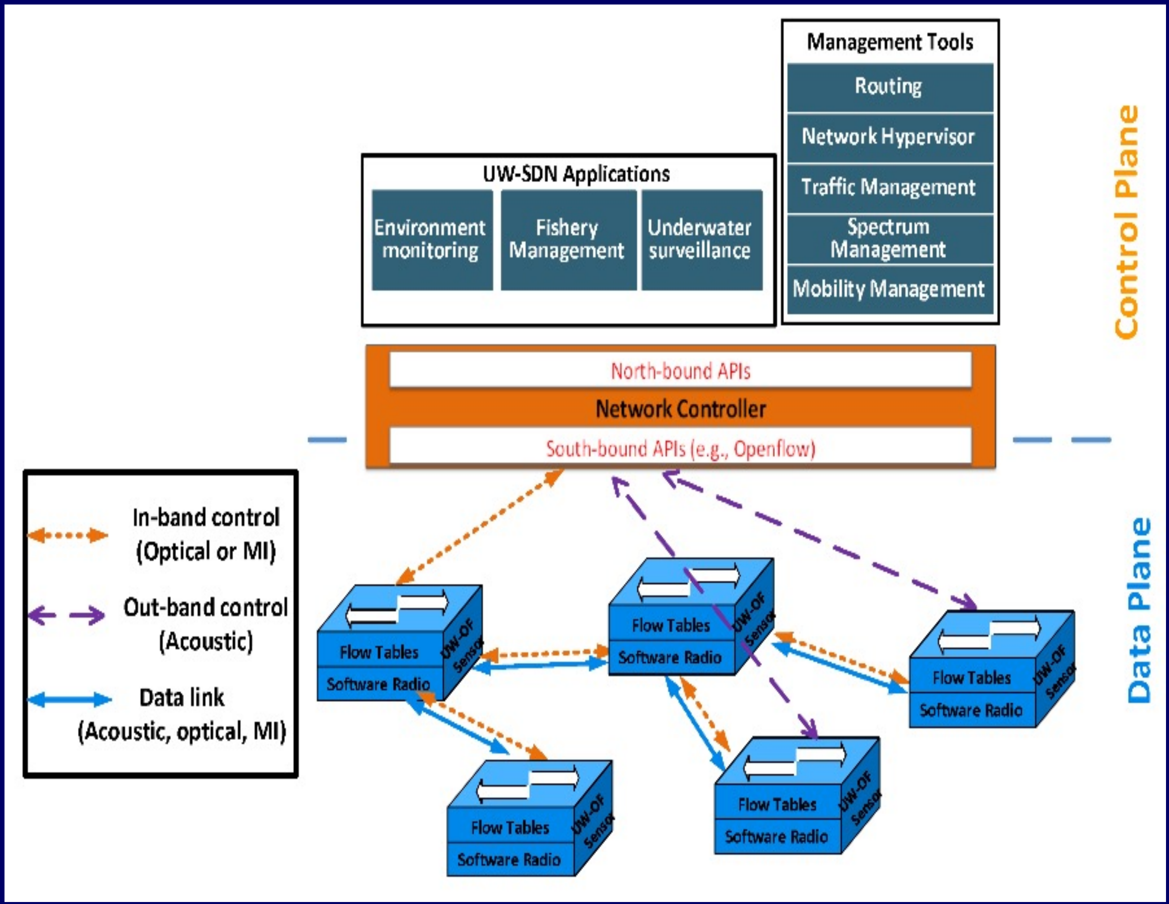
I.F. Akyildiz, P. Wang and Shih-Chun Lin,
"SoftWater: Software-Defined Networking for Next-Generation Underwater Communication Systems",
Ad Hoc Networks (Elsevier) Journal, pp. 1-11, April 2016.

SoftWater: SDN Architecture for Underwater Communication

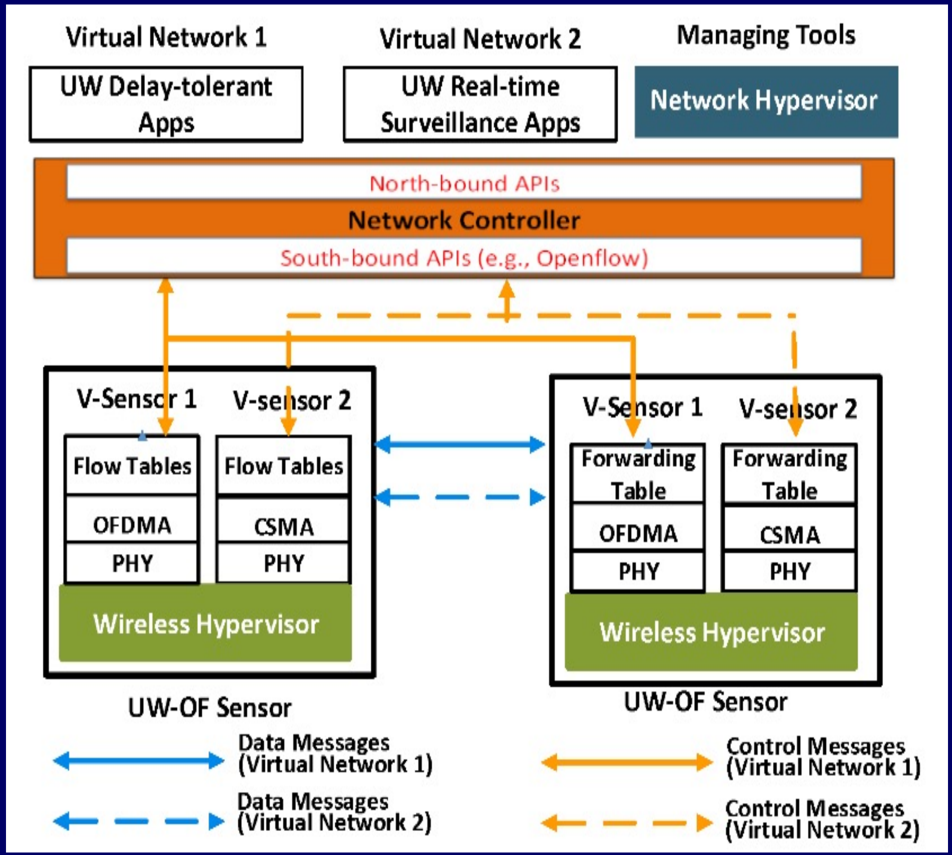
I. F. Akyildiz, P. Wang and Shih-Chun Lin,
"SoftWater: Software-Defined Networking for Next-Generation Underwater Communication Systems",
Ad Hoc Networks (Elsevier) Journal, pp. 1-11, April 2016.



SoftWater: Software Defined Underwater Networks



SoftWater: Network Function Virtualization



SoftWater: OBJECTIVES

I. F. Akyildiz, P. Wang and Shih-Chun Lin,
"SoftWater: Software-Defined Networking for Next-Generation Underwater Communication Systems",
Ad Hoc Networks (Elsevier) Journal, pp. 1-11, April 2016.

SoftWater Architecture

* Scalable Architecture Design
* Network Function Virtualization (NFV)

Managing Tools

* Control Traffic Balancing
* Network Virtualization
  * Network Hypervisor
  * Wireless Hypervisor

TE Solutions

* Collaborative Resource Management
* UAV Mobility Management

Plethora of Open Research Issues

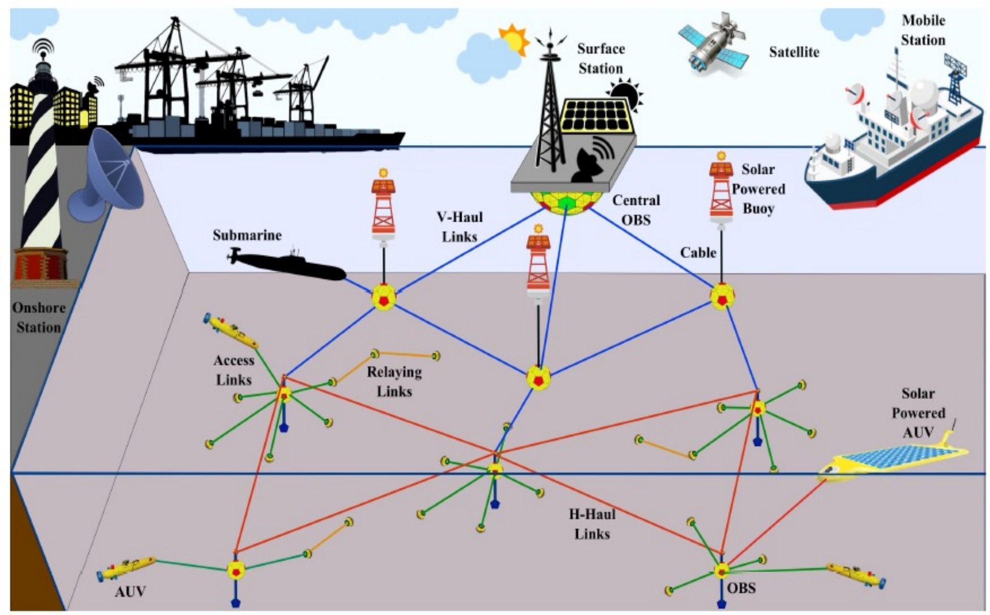
- Optimal underwater SDN planning (e.g., optimal controller placement)
- Control traffic balancing (e.g., optimal hybrid in-band & out-band control)
- Software-defined traffic engineering for scalable underwater networking
- Software-defined AUV mobility management
- Cost-efficient and automatic NFV?

CHALLENGE 5: UNDERWATER OPTICAL MARINE COMMUNICATION

V-HAUL: Vertical Haul (Long Hall) Optical Links
H-HAUL: Horizontal Haul (Short Hall) Optical Links
OBS: Optical Burst Switch

Challenges

- Insufficient data rate
- High attenuation
- Requirement for real-time operation



Optical waves have the advantage of higher data rate, low latency, and power efficiency at the expense of limited communication ranges.

Advantages of Optical UW Channels

- High BW; higher data rates; longer distances (few hundred meters)
- High frequency of the optical carrier allows for higher BW
- Low-latency can be achieved because of negligible propagation delays
- Small-size transceivers
- Un-tethered (wireless) connection between transmitter and receiver
- Stealth operations are more efficient than in the EM and acoustics paradigms

Challenges of Optical Communication for Underwater

- Transceivers (Lasers and Photodiodes) must be perfectly aligned
- Misalignment of the transceivers can cause short-term disconnections
  - Because of andom movements of the sea surface, depth dependent variations and deep currents, and oceanic turbulences.
- Light beam propagation undergoes absorption, scattering, and multipath fading because of the interactions of water molecules and particulates with the photons

FUTURE RESEARCH DIRECTIONS IN OPTICAL COMMUNICATION

- UOWC Modeling and Analysis
- Novel Network Protocols
- Cross layer design issues
- Localization
- Practical Implementations
- Energy Harvesting
- Reduction of Equipment Costs

CHALLENGE 6: UNDERWATER QUANTUM COMMUNICATIONS

- **Primary motivation for UW quantum communications comes from the need for perfectly secure communication systems, esp. for military**
- **While, quantum communications has been prototyped widely across optical transmission mediums, and even satellites, the UW channel is yet to be utilized for this purpose.**

UNDERWATER QUANTUM COMMUNICATIONS:
OPEN RESEARCH CHALLENGES

- **Analytical Channel Models:**
  - UW quantum channel characterization has been only experimental in nature, necessitating a need for accurate analytical channel models to further study the feasibility of UW quantum communications.

- **Accurate Link Budgets:**
  - Impact of optical properties of oceanic waters are not well understood yet, thus requiring more research efforts in this direction.
  - Further, the effects of UW turbulence on the optical links also need to be studied in detail.

UNDERWATER QUANTUM COMMUNICATIONS:
OPEN RESEARCH ISSUES

- **Protocols and Algorithms for Quantum Communication in Underwater**

- **Deployment Challenges:**
  - Quantum communications devices require highly specialized data centers equipped with ultra-high vacuum systems and ultra-low temperature cryostats.

  - Such infrastructural requirements are extremely difficult to meet in the UW environment.

CHALLENGE 7:
ENERGY HARVESTING IN UNDERWATER SYSTEMS

- **Energy constraints in UW environment:**
  - Frequent replacement of UW devices → Time consuming and expensive
  - Prior art mainly focused on energy conservation:
    - In-network processing
    - Dynamic voltage scaling
    - Energy-aware communications
  - Underlying problem still remains → Devices eventually run out of energy
  - Possible solution: Energy Harvesting

Underwater Energy Harvesting

- **Solar Energy:**
  - Underwater photovoltaic cells limited to 10m depths
  - Low efficiency
- **Tidal Energy:**
  - High infrastructure and operating costs
  - Limited reliability

* Acoustics resonators and microbial fuel cells are used to harvest energy

Existing Approach

V. Bana, M. Kerber, G. Anderson, J. D. Rockway and A. Phipps,
"Underwater wireless power transfer for maritime applications,"
2015 IEEE Wireless Power Transfer Conference (WPTC), Boulder, CO, 2015.

- **Underwater Power Cables**
  - Requires additional energy harvesting infrastructure
  - Impractical for large and remote networks
  - Defeats purpose of wireless sensors

- **Underwater Wireless Power Transfer through MI**
  - Stationary battery controller on surface harvests energy
  - Wireless power transfer to underwater sensors
  - Charging efficiency drops to 0% beyond 30 cm

Piezoelectric Energy Harvesting Approach

- Use of Piezoelectric Bimorphs (actuator) to harvest energy from water kinetics (perpetually moving water currents)

- AUVs equipped with:
  - Photovoltaic Cells: Harvest solar energy to power AUVs
  - Piezoelectric Bimorphs: Harvest energy in water kinetics to recharge UW devices

- SoftWater SDN/NFV framework:
  - Surface controllers (buoys) determine optimal AUV routes

Energy Harvesting Model

- **State of AUV:**
  - **Recharge:** AUV has sufficient energy, will recharge assigned UW device
    Resurface: AUV is low on energy, resurface to charge its photovoltaic cells
  - **Stay put:** AUV has sufficient energy, but no UW device in vicinity needs charging

- **Controller assigns AUV state based on:**
  - Energy levels of devices in vicinity
  - Energy level of AUV
  - Distance to least energy UW device

CHALLENGES: OPTIMIZATION ALGORITHMS NEED TO BE DEVELOPED !!!

SOME COMMERCIAL ACOUSTIC MODEMS

- Teledyne Benthos http://www.teledynemarine.com/benthos/
- Link Quest https://www.link-quest.com/
- EvoLogics (Germany) https://evologics.de/
- DSPComm (Australia) → AquaComm ad AquaNetwork https://dspcommgen2.com/
- TriTech https://www.tritech.co.uk/product/micron-data-modem
- Popoto (https://popotomodem.com/)
- Develogic (http://www.develogic.de/)
- Blueprintsubsea (https://www.blueprintsubsea.com/pages/index.php)
- Applicon http://www.applicon.it/index.php?option=com_content&view=article&id=5&Itemid=728
- Subnero https://subnero.com/

EXPERIMENTAL TESTBEDS

- LOON (Littoral Oceanographic Observation Network)
  - NATO CMRE (Center for Maritime Research & Experimentation)
    https://www.cmre.nato.int/
- SeaWeb Project
  - Funded by Office of Naval Research
- CMRE NATO
  - Center for Maritime Research and Experimentation