Underwater Communications: Recent Advances

Mohammad Furqan Ali*, Dushantha Nalin K. Jayakody*†, Tharindu D. Ponnimbaduge Perera*,
Kathiravan Srinivasan‡, Abhishek Sharma§ and Ioannis Krikidis¶
*School of Computer Science and Robotics, National Research Tomsk Polytechnic University, RUSSIA
†School of Postgraduate Studies, Sri Lanka Technological Campus, Sri Lanka
‡ School of Information Technology and Engineering, Vellore Institute of Technology, INDIA
§Department of Electronics Communication Engineering, The LNM Institute of Information Technology, INDIA
¶Department of Electrical and Computer Engineering, University of Cyprus, Cyprus
Email:[ali89,ponnimbaduage,nalin]@tpu.ru, kathiravan.srinivasan@vit.ac.in, abhisheksharma@lnmiit.ac.in.

***Abstract*—Our earth the only planet where water could be found and covered more than seventy percent with it. Monitoring different phenomenal activities in an underwater environment, such as environmental impact surveillance, marine life, oil and gas exploration is essential in underwater. In this regard, underwater wireless communication (UWC) has become a significant field. Optical, acoustic and electromagnetic waves have been widely used for data transmission in UWC. Investigation of possible UWC techniques has an influential impact on wireless communications. Nowadays, UWC is being used for experimental observation, oceanographic data collection and analysis, underwater navigation, disaster prevention and early detection warning of a tsunami. This work presents an overview, main initiatives and up-to-date contributions of the most widely used UWC techniques, i.e, underwater wireless optical, acoustic and electromagnetic communications. In addition, we summarize emerging technologies in the UWC, future research directions and recommendations using fifth generation (5G) communication techniques.**

***Index Terms*—Underwater wireless acoustic communication, Underwater electromagnetic communication , Underwater optical communication, 5G wireless communication.**

I. Introduction

Global warming has become an issue for several decades. In rising of global warming, the polar ice caps melt gradually cause of rising sea level. Hence, the importance of observing ocean environmental activities such as oceanographic data collection, water sampling, etc., has gradually increased with time variation. Underwater Wireless Communication (UWC) supports surveillance of coastal securities, especially for military purposes and commercially for investigation of natural resources in underwater environment. Moreover, it also helps for mapping and discovering the unknown regions of underwater. Nowadays, UWC is being used for experimental observation, data collection, and analysis, underwater navigation, disaster prevention and early detection warning of tsunami [1]. Optical, acoustic and electromagnetic (EM) wireless carriers are considered to envisage UWC in underwater applications. Deploying UWC techniques in an unexplored water medium are highly challenging as compared to terrestrial wireless communication [2]. However, the quality and reliability of data transmission in shallow and deep water are dependent on the physical characteristics of the water channel [3]. The Quality of Service (QoS) of UWC, depends on the physicochemical properties of water medium and physical characteristic of optical, acoustic and EM waves. UWC plays a significant role in deployed underwater applications, which has an influential impact on the wireless network. The deployment of communication network setup in underwater systems consist of fixed and anchored sensor nodes with the seabed, floating unmanned underwater vehicle nodes (UUVs) or autonomous underwater vehicle (AUVs), signal receiver processing towers, floating devices (buoy), submarines, ships and onshore base stations [4].

EM waves in radio frequency (RF), 3Hz to 3 kHz frequency range is capable for high data acquisition and transmission in shallow water over short distances and usually attenuated easily by seawater [4]. On the other side, acoustic waves are affected by different propagation factors due to ambient noise, external interference, water-surface geometrical expansion, attenuation, multi-path effects, and Doppler spreading. Optical waves have high bandwidth, but affected by absorption, scattering and different level of temperature in underwater. Underwater wireless optical communication (UWOC) has less explored and somewhat challenging to deploy than acoustic propagation in underwater [5]. The existing Underwater wireless acoustic communication (UWAC) has the limited performance of low bandwidth, latency and multi-path propagation in an underwater medium. The maximum data acquisition in UWAC is roughly 100 kbps for short distances while 10 kbps over long distances. The possible bandwidth with respect to propagation distance in UWAC are listed down in Table I.

The main purpose of this survey is to understand the main characteristics and existing features of UWC. This work has an overview of possible UWC techniques and up-to date literature. The remaining structure of this paper as follows: In section II, we discuss the main deployable techniques of UWC towards the next generation of wireless network. Underwater wireless RF communication (UWRFC) and related issues are described in section III. Underwater wireless optical communication (UWOC) has been widely discussed in section IV. In section V, underwater wireless acoustic communication (UWAC) and it's issues are discussed. The paper contributes emerging communication techniques proposed by recent research in section VI. Finally, we conclude the paper in section VII.

Classified Propagation distance	Possible range (km)	Maximum bandwidth (Hz)	Possible data rate (kbps)
Very Sort	Less than 0.1	More than 100	500
short	0.1 to 1	20 to 50	30
Medium	1 to 10	Up to 10	10
Long	10 to 100	2 to 5	5
Very long	more than 100	Less than 1	600

TABLE I
THE POSSIBLE BANDWIDTH FOR DIFFERENT ACOUSTIC PROPAGATION DISTANCES [6]

II. The integration of 5G in underwater communication

5G wireless network will be the future networking technique in wireless communications with extremely low latency and high data rate [9] [10]. A high range acoustic communication through orthogonal frequency-division multiplexing (OFDM) techniques has been discussed in [11]. The authors [3] discussed UWC techniques and its' related issues along with the UWC emerging technologies. Filter bank multicarrier (FBMC) and generalized frequency division multiplexing (GFDM) are the latest promising techniques for 5G applications in underwater environment. GFDM is a multicarrier scheme that based on time and frequency, which is derived from filter bank approach [12]. FBMC also addresses both time and frequency dispersions that should be constructed by using prototype filter. The parametric constraints should matches channel properties [13]. An experimental work on GFDM technique towards underwater 5G communication systems based on multi-carrier filter bank has been discussed in [12]. The concept of adopting MIMO-OFDM for underwater acoustic channel and using FBMC modulation technique towards 5G wireless network investigated in [14].

A. Types of water in UWC

The seawater has been categorized into three different categories in UWC, i.e, clearest, intermediate and murkiest water [15]. The clearest water is the most transparent water, which could be found in Atlantic and Mid-Pacific ocean. Secondly, intermediate water can be found in North Pacific ocean. The murkiest water can be found typically in the Northern Sea and Eastern Atlantic ocean. Due to optical propagation, seawater has been divided into four categories due to optical inherent properties (IOP) [6] i.e. pure seawater, clear ocean water, coastal ocean water, turbid harbor and estuary water. Typical values of absorption and scattering coefficients in different waters are listed-down in Table II.

Absorption and scattering of signals play a major role in deciding QoS in UWC. In optical signal propagation, the scattering losses arise due to the high particle concentration in clear ocean water while the absorption and other major

Description of water for UWC	a(λ)	b(λ)	$b_b(\lambda)$	c(λ)
Pure sea water	0.053	0.003	0.0006	0.056
Clear Ocean water	0.069	0.08	0.001	0.15
Coastal Ocean water	0.088	0.216	0.0014	0.305
Turbid Harbor water	0.295	1.875	0.0076	2.17

TABLE II
TYPICAL VALUES OF ABSORPTION AND SCATTERING COEFFICIENTS IN DIFFERENT WATER MEDIUMS [5]

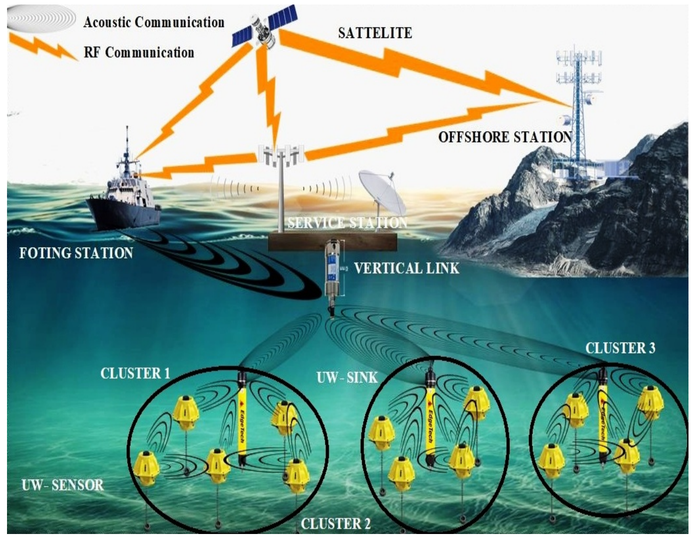

Fig. 1. Acoustic and RF signal propagation between underwater sensor nodes and terrestrial offshore station

losses occur in pure seawater. The higher concentration of suspended particles in ocean water support to scattering and absorption phenomena and affect to signal propagation. The highest concentration of particles could be found in turbid harbor and estuary water than pure and clear ocean waters.

III. Underwater RF Communication

EM waves used for signal transmission between underwater and terrestrial communication platforms [16]. EM waves covers frequency ranges from few kHz to 1 GHz [17]. EM waves propagation setup deploy for shallow water over tens of meter called by RF buoyant underwater communication [6]. The possibility of RF signal propagation is higher in shallow water than deep ocean water. The oceanic water offers high conductance which could be seriously affected to electromagnetic wave propagation [3]. Thus, very less possibility is available to establish communication over long distance in the underwater environment, with ultra-high frequency and very high-frequency ranges (VHF and UHF), or even in high-frequencies (HF). The electromagnetic waves attenuation considered to be lower enough to achieve expected communications over several kilometers in underwater environment [4]. Thus, the multiple-path propagation could be an additional benefit for underwater signal transmission in inland water reservoirs, i,e lakes, rivers, etc. from submerged communication nodes to

Types of Technology	Distance	Propagation Speed(m/s)	Frequency	Bandwidth	Data rate	Attenuation	Affecting factors determine channel quality	Reference
RF	Very short distance (Up to 10 m)	2.255x10^8	30-300 Hz	MHz	Mbps	Frequency and conductivity dependent (3.5-5 dB/m)	Conductivity and permitivity of channel	[2] [4] [7] [6] [8]
Optical waves	Short distances (Up to 100 m)	Almost same as RF (2.255x10^8)	10^{12} -10^{15}Hz	MHz	Gbps	0.39 dB/m (Ocean) and 11 dB/m (Turbid water)	Absorption, scattering, turbidity, suspended and organic matter of channel link	[2] [4] [7] [6] [8]
Acoustic	Long distance (Up to 20 km)	1500	10-1 kHz	Hz	kbps	Distance and frequency dependent (0.1-4 dB/m)	Absorption, scattering, pressure, temperature and salinity of water medium	[2] [4] [7] [6] [8]

TABLE III
COMPARISON AMONG DEPLOYED UNDERWATER WIRELESS COMMUNICATION TECHNOLOGIES

onshore base stations [18]. In UWRFC, signals experience high attenuation than in terrestrial communication.

In UWRFC, EM wave propagation depends on underwater environment. The physical properties of the water, i.e., salinity, conductivity, and temperature affect electromagnetic propagation in underwater [19]. In seawater, the average value of conductivity approximately 4 mhos/m, which is doubled in the magnitude of conductivity in freshwater [6]. The absorption coefficient in seawater can be expressed as [19].

$$\alpha(f) = \sqrt{\pi \sigma \mu_0 f}, \tag{1}$$

where radio frequency denotes by f and σ represents the conductivity of the water. The vacuum permeability describes by $\mu_0 \equiv 4\pi 10^{-7}$ H/m. The value of μ_0 is almost equal in fresh and seawater [4]. A typical channel model transfer function for different channel parameters is widely discussed in [19].

A. Main issues in underwater RF communication

EM waves are affected by several factors depend on the water properties, such as density level, which can vary with temperature, high permittivity, electrical conductivity, and salinity. In addition EM waves also affected by turbidity in underwater and by the various types of noises. In UWRFC, multi-path propagation is the most influential phenomena that has a direct impact on RF propagation from water to air. The refraction angle and losses also have a consideration in RF signaling to cross the air-water boundary by patching through an antenna [4]. Electromagnetic waves used for a limited range of communication in underwater, which could be raise for over long ranges by implementing a specific design of an antenna. A large size antenna is required for RF signal propagation between terrestrial and underwater communication. The magnetic coupled loop types of antennas are the most reliable for practical solutions. An another option is to use an electric dipole antenna for lateral electromagnetic waves that has been discussed in [18]. In the deployment of UWRFC propagation scheme, major factors to be considered are high data rate, the antenna design and transmitting power strength.

IV. OPTICAL COMMUNICATION

UWOC has many distinct properties during propagation at different frequencies over different ranges in dissimilar water mediums [8]. The light speed might be around four to five times stronger and higher in magnitude than propagation speed of acoustic waves in fluids [4]. The sea water offers a conductive property for RF propagation and dielectric properties for optical signal propagation [4]. Optical communication is affected by scattering, dispersion, line of sight (LOS), fluctuation in temperature and by physiochemical properties of the water. In dielectric medium, the possibility to achieve high data rates through UWOC technology as compared to UWRFC, where the range of propagation limited up to tens of meters [4]. In addition, the negotiation of Doppler effect can be obtained in optical communications as compare to competitive schemes, i.e., EM, acoustic.

According to the environmental conditions, the sea water has been categorized into two specific categories, inherent optical properties (IOP) and apparent optical properties (AOP) in respect with optical propagation. IOP is medium dependent, while AOP is light source dependent [20]. In optical propagation, photons change their direction due to scattering and the possibility of scattered photons originated by salt ions in pure water [20]. In UWOC propagation, the beam attenuation coefficient is directly related to the intensity and separation distance of light sources. The light intensity at receiver end can be expressed as [21].

$$I = I_0 \exp^{-cd\lambda}, \tag{2}$$

where I_0 and I are the light intensities both of transmitter ends and receiver, d denotes the distance between transmitter and receiver.

A. Noises in underwater optical communication

There are different types of noises in UWOC such as quantum shot noise, optical excess noise, optical background noise, photo-detector dark current noise and electronic noise [22].

- The Quantum noise: This type of noise occurs due to receive random variation of photons by optical receiver.
- The Optical excess noise: The Optical excess noise caused due to transmitter imperfection.
- The Background noise: In this type of noise the background consider as a blackbody radiation in underwater

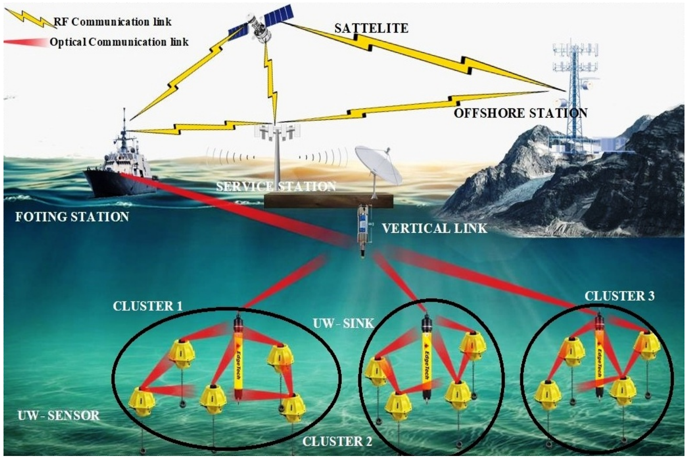

Fig. 2. Illustration of Underwater optical sensor network clusters with terrestrial RF based station

- whose primary source is the refracted sunlight from the water surface. Due to this phenomena, the solar and blackbody radiation background noises occur.
- The Photo-detector dark current noise:- Due to electrical current leakage from photo-detector this kind of noise occurs.

B. Main Issues in optical communication

Absorption and scattering are the two crucial effects that affect the propagation of optical waves in underwater [7]. We can understand the simple phenomena of these two factors by the geometrical model of a water element that has shown in Fig. 3. If the input beam of light strength $P_i(\lambda)$, the small fraction of incident beam $P_a(\lambda)$ absorbed and fraction $P_s(\lambda)$ scattered by water element. The unaffected result $P_c(\lambda)$ passing through water element whose volume is δV and thickness δr respectively. According to energy conservation balancing, the absorption and scattering phenomena can be described as [6].

$$P_i(\lambda) = P_a(\lambda) + P_s(\lambda) + P_c(\lambda). \tag{3}$$

The overall attenuation in underwater coefficient c(λ) can be expressed as [7].

$$c(\lambda) = a(\lambda) + b(\lambda). \tag{4}$$

The values of a(λ) and b(λ) in different water medium could be found from Table II.

V. ACOUSTIC COMMUNICATION

UWAC is an alternative communication technique which can be used for longer distance communication than UWRFC and UWOC. However it has a limited range of propagation and is affected by strong attenuation and water turbidity. Acoustic waves propagation offers low frequency, bandwidth and low speed around 1500 m/s. The propagation of acoustic waves is faster in normal water than cold water [3]. Generally, the speed increase of acoustic waves about 4 m/s, due to rising of

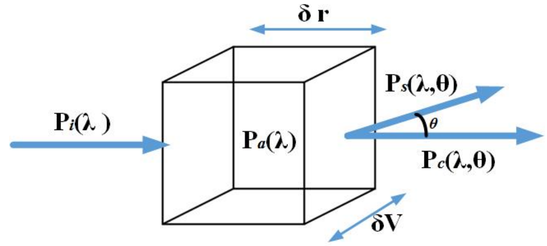

Fig. 3. Optical wave scattering and absorption phenomena in underwater as given in [6] [8]

1°C temperature in water. According to the acoustic waves propagation range, the water channel has been categorized very short, short, medium, long and very long propagation distances [6]. In Table I, mentioned the different bandwidth ranges according to the propagation range. An acoustic model for sound speed profile (SSP) has been discussed for underwater communication environments with 1 km of water depth [23].

$$\begin{aligned} c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 \\ +(1.34 - 0.01T)(S - 35) + 0.016z, \end{aligned} \tag{5}$$

where c denotes acoustic wave speed and T is channel temperature, S represents the salinity of water and water depth denotes by z. Thus, the acoustic waves speed is a function of channel temperature, depth and salinity of water which can be proportional to water temperature, salinity and depth of water medium [24]. Due to high absorption and frequency, wave energy converts into heat energy. Similarly, longer propagation ranges lead to high absorption losses [25]. The absorption coefficient is the sum of absorptivity and contribution of chemical reaction by the water medium [26] [27]. Similarly, scattering loss occurs due to obstacles during acoustic wave propagation. These obstacles can be consider by the disturbance at sea surface, existing fixed or movable objects at the bottom of sea. Spreading and absorption losses contribute path loss, whose explained by a simplified model expressed by [25] [28].

$$\begin{aligned} 10\log A(l,f) = 10\log(A_0) + 10k\log(l) \\ +(l) * 10\log a(f,S,T,c,p,H,z), \end{aligned} \tag{6}$$

where l denotes the distance (in meters) or propagation range between transmitter and receiver, f is the frequency range (in kHz) and k denotes the spreading factor. For cylindrical spreading the value of $k = 1$, while for spherical spreading $k = 2$, the value of $k = 1.5$ can be taken for experimental spreading [25]. Log A_0 is called normalizing factor which is the inverse of transmitted power. The variables are representing the attenuation coefficient (in dB/meter), depend on environmental channel conditions [28]. The variable S represents salinity (in ppt), temperature denotes by T (in degree Celsius), and c is the speed of acoustic wave propagation (in m/s), z and H are showing the depth of water in meters. The path losses expand when the frequency f and separation distance d between transmitter and receiver increase.

A. Most common Issues in underwater acoustic propagation

The main issues in underwater acoustic propagation that affect communication links through man-made noises, path and multi-path losses, Doppler spread, high and variable propagation delay. Above mentioned losses and factors determined the temporal and spatial variability of the acoustic channel that cause of limited communication range, frequency and bandwidth of acoustic communication link. The following factors are effective issues on acoustic communication.

- Losses: The main factors can be taken into an account while signal propagation energy losses, absorption and scattering loss respectively.
- Man-made and ambient noise: Ambient noise related to hydrodynamics properties of water such as an underwater thunderstorm, water movement, water tides, water bubbles and fain, wind, rain and biological phenomena. The ambient noise losses up to 26 dB/km [29]. Man-made noises produced by machine tools such as pumps, power plants, submarines and ships etc.
- Attenuation: Attenuation occurs by absorption of the acoustic energy that transforms into heat, scattering, refraction reverberation phenomenon, and dispersion. Acoustic waves attenuation is directly proportional to the frequency of waves and depth of water medium.
- Absorption: The energy conversion phenomena of acoustic waves in another form of energy by chemical characteristics of the water channel.
- Geometric expansion: Geometric expansion is a spreading experience and function of energy loss in acoustic waves over the large area. When the acoustic pulse propagates from source of origin and covers a large water area, the wave energy per unit area become smaller.
- Path and multi-path propagation losses produced by the degradation of acoustic waves, generates Inter-Symbol Interference (ISI). The multi-path propagation are the geometrical constraints and configuration link dependent. In Vertical channels develops a little time dispersion but through water layers, it has a long multi-path spread, which is depends on water depth.
- Doppler frequency spread is an important and noticeable factor in UWAC, due to a low destruction in the performance of digital communication and transmission at high data rate [8].

VI. Emerging Underwater Communication Technologies

A. Energy Harvesting

Energy harvesting (EH) is an approach to capturing and transformed usefulness energy into usable electric power where energy requires in terms of heat, vibration and RF signals. Underwater wireless sensor network (UWSNs) is an emerging technique to establish reliable data although required high energy constraints. The wireless power transmission (WPT) technique is promising EH technique. In WPT the nodes capable to charge their own batteries sources through electromagnetic radiation in remote networking area [30]. WPT offers a good performance for short distances while it depends on application requirement for long distance. The authors [30] proposed simultaneous information and power transfer EH technique (SWIPT) that enables to transfer information and power simultaneously. These investigated techniques support to improve efficiency of system.

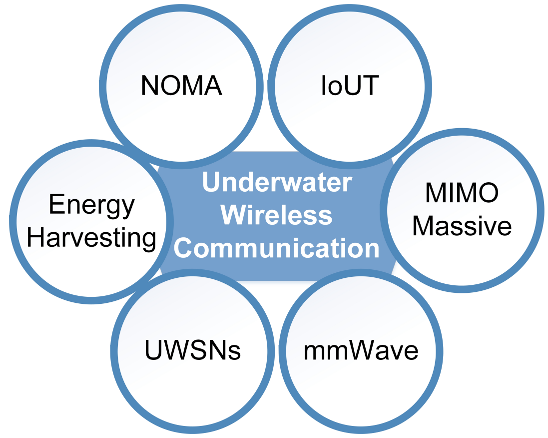

Fig. 4. Emerging Underwater Wireless Technologies

B. Massive MIMO adaptive Underwater Communication

Massive multi-input-multi-output (MIMO) supports underwater acoustic communication through large number of hydrophones array. It also support the various types of multimedia communication contents in real time activities and audio-video conferencing [31]. Massive MIMO is an auspicious solution that support to improve throughput, capacity and energy efficiency of UWC system in the future.

C. mmWaves enabling Underwater Communication

Due to high demand of improving communication networking capacity, mmWaves are an alternative solution to support underwater communication. These waves offer likely similar characteristics to the optical wireless signals. Hence mmWaves are considering to offer high bandwidth transmission and efficiency to improve communication performances [32]. The waves are capable to provide up to 10 gbps data rates which is the solution of hybrid communication [33].

D. Non-Orthogonal Multiple Access (NOMA) as an emerging wireless carrier

Non-Orthogonal multiple access (NOMA) offers desirable communication benefits and a promising multiple access technique. It allows to connect multiple users simultaneously and minimize delay. The future acpect of NOMA expected allocation schemes in Underwater acoustic networks architecture (UWASNs) and equal transmission times (ETT) power allocation which are capable to prevent the wasteful resources generation in underwater environment that proposed for the future perspectives [34].

E. Internet of Underwater Things (IoUTs)

Internet of things is an emerging technology that offers to connect devices wirelessly. The integration of Internet of Underwater Things (IoUTs) plays a significant role to allow data exchange between UWSNs to the base station in underwater environment. IoUTs provide an opportunity to observation of marine life and understanding of underwater habitats [35].

VII. Conclusion

UWC technology enables a platform to build up a network connection between underwater devices with offshore based station. The main motto of this paper to provide an overview and challenges posed by the peculiarities of underwater communication technologies with particular reference to monitoring applications in water medium. The different water channels and communication links have crucially difficult properties and challenges. The technologies discussed, the possible solutions and grasp to deploy underwater wireless acoustic, underwater wireless electromagnetic and underwater optical wireless communication technologies. The main outline of this paper to encourage research efforts and development of new advanced communication techniques. This paper has been contributed and providing a survey of the technical issues and challenges in underwater networks and communication of entire technologies towards the next generation wireless networking system.

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