

Multimodal Underwater Networks: Recent Advances and a Look Ahead

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ABSTRACT

The recent uptake of non-acoustic underwater transmission systems suggests that in the near future it will be common for underwater devices to incorporate different physical communication technologies. Such devices are typically described as *multimodal*. They seek flexibility by compensating for the shortcomings of a given technology through the advantages of another. For example, a system encompassing acoustic and optical communication systems can provide long-range, low-bit rate communications, while enabling faster data transfer at very short range.

As the development of non-acoustic underwater communications is taking momentum, so is the research on how to optimally exploit the multimodal communications capabilities in different scenarios. This paper presents a survey of past and recent work on this topic, covering the development both of the communication technologies and of the networking schemes and protocols for multimodal networks. As an example of the opportunities offered by multimodal communications, we discuss two different case studies. We conclude with an outlook on likely future developments for multimodal communications.

KEYWORDS

Underwater acoustic networks; multimodal communications; survey; case studies; outlook; field experiments

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1 INTRODUCTION

When referring to underwater communication and networks, it is usually implied that acoustic technologies are employed for wireless information transfer. Indeed, acoustic communication schemes and systems have been widely researched and studied, and many practical modem implementations and commercial products exist that deliver acoustic communications for general-purpose or niche applications [1].

Acoustic modems are generally characterized by a convenient mix of long transmission ranges, fair reliability and robustness. These features vary depending on the application. For example, in high-reliability scenarios, the user is more willing to sacrifice the link data rate in favor of better protection against channel distortion and errors. On the contrary, non-mission critical high-rate transmission operations such as underwater habitat inspection and surveying may require the transmission of bulk data in the form of underwater video or images, which may be carried out in quasi-real time through a modem that provides a sufficiently high bit rate at the price of lower reliability.

Owing to the advancement of acoustic telemetry and communications [2–4], to their capability to cover different scenarios, as well as to the establishment of the first underwater communication standard [5–7], acoustic communications have become a de-facto solution for several applications, from biology, oceanography and meteorology, to coastal surveillance, anti-submarine warfare, and ecological relief operations. Still, underwater acoustic links are typically limited in terms of bandwidth (which decreases with the maximum coverage distance), and resilience to multipath distortion. Moreover, high bit rates become available only in specific scenarios, and typically over short-range, benign channels. To overcome these issues, other underwater communication technologies based on, e.g., optical [8–16], radio-frequency [17–19] or magneto-inductive signals [20, 21] have been considered. Each of them comes with its

own pros and cons: for example, optical signals achieve extremely high bit rates within very short reach (up to a few meters, or a few tens of meters in dark and clear waters), whereas radio-frequency signals incur very strong attenuation in conductive ocean waters, but achieve reasonable bit rates at short range (higher than acoustic systems within a few meters) and are not affected by misalignment issues, unlike optical links.

Given the interest in the development of diverse technologies for underwater scenarios, it has recently been proposed that communication devices may incorporate multiple, non-mutually-interfering transceivers, possibly involving multiple technologies [22–25], into what is referred to as a *multimodal communication system*. This makes it possible for each node to leverage more flexibility in face of a changing communication context, at the price of a generally bulkier system prototype, that requires further integration efforts and additional logic to exploit the advantages of each technology. Relevant examples, in this respect, include the utilization of underwater optical and acoustic communications to enable very high-rate data transfer at short range, or the integration of bandwidth-disjoint acoustic systems that cover, e.g., both high-rate short-distance and low-rate long-distance communications.

In this paper, we provide an overview of recent advances in the domain of multimodal underwater communications and networks. We proceed by reviewing the state of the art in Section 2 (both for physical communication technologies per se, and for their integration into multimodal networks) and provide two relevant examples of how these technologies can be integrated to provide substantial advantages in two specific case studies (Section 3). We then provide our own outlook into the future evolution of underwater multimodal communications and draw concluding remarks in Section 4.

2 STATE OF THE ART ON MULTIMODAL COMMUNICATIONS AND NETWORKS

2.1 Underwater communication technologies

The large number of applications that can be potentially supported by underwater acoustic communications has prompted the research and commercial development of several acoustic transceivers. Until recently, such transceivers used to be mostly optimized for long-range communications at a low bit rate. For example, the Benthos ATM 90 [26] can transmit up to 2.4 kb/s at 6 km and 15 kb/s at 1.5 km; the LinkQuest UWM series covers from 1.5 kb/s at 5 km to 17.8 kb/s at 1.5 km; the EvoLogics S2CR 7/17 modem [27] can achieve a coverage range of up to 8 km with a maximum bit rate of 6.9 kb/s; the AQUATEC AQUAmodem1000 [28] has a maximum transmission range of 10 km with a data

rate of 100 b/s to 2 kb/s; the Sercel MATS3G [29] covers 2.3 km at 16.5 kb/s, or 16.5 km at 100 b/s; and the Develogic HAM.NODE [30] can transmit up to 30 km with a bit rate of 145 b/s. Further, it has been shown that it may be possible to achieve a communication link of 100 to 400 km at 1 b/s in the Arctic [31] using the WHOI MicroModem [32].

Over the last ten years, underwater acoustic communications have emerged also as a practical solution for telemetry, where a higher bandwidth is required for communication at intermediate, order-of-km ranges. Several solutions for this application are available off the shelf, such as the EvoLogics S2CR 18/34 modem [33] (13.9 kb/s at up to 3.5 km), and the Subnero modem [34] (15 kb/s at up to 3 km). Short-range acoustic communication systems were typically restricted to research purposes. For example, the Hermes FAU acoustic modem [35] is reported to achieve a bit rate of 87 kb/s up to 120 m, whereas MIT developed a prototype able to achieve more than 100 kb/s up to 200 m in a controlled scenario [36]. Despite the research efforts, neither of [35, 36] has developed into a commercial prototype.

Only very recently did short range underwater communications start to be of interest. This is mainly due to an increasing number of foreseen applications for underwater scenarios, with special reference to those involving one or more submerged vehicles that exchange high-rate data streams with fixed nodes or human controllers, and therefore require short-range, high-rate underwater communication systems. Very promising prototypes and some off-the-shelf high-rate acoustic modems have been developed along these lines. Northeastern University developed the SEANet modem prototype [37], able to transmit 41 kb/s. Given the current hardware specification, they estimate that the prototype should be able to reach a data rate of 250 kb/s by utilizing a bandwidth of 100 kHz at a range of a few meters. BaltRobotics demonstrated low-quality video streaming with their acoustic prototype [38], which communicates at 115 kb/s within a range of up to 200 m. EvoLogics also developed their S2CM HS modem [39], which achieves 63 kb/s up to 300 m.

Although acoustic modems are the typical solution for digital underwater digital communications, alternative technologies are being studied that may fit better in some scenarios. For instance, electro-magnetic (EM) radio-frequency (RF) and magneto-inductive (MI) underwater modems are able to perform broadband communication at very short range. The Wireless for Subsea (WFS) Seatooth S500 [42] RF modem provides a bit rate up to 100 Mb/s up to a range of 10 cm. This modem can be employed in docking stations to quickly download data from an autonomous underwater vehicle (AUV) with no need for physical cables [43]. Similarly, the INESC Tec institute of the University of Oporto, developed a dipole antenna prototype [18] to support 1 Mb/s communication at 1 m, and the Lubeck University of Applied

Table 1: List of performance figures for representative acoustic, EM/RF/MI, and optical underwater transceivers

Tech	Manufacturer and model	Range	Bit rate	Tech Pros	Tech Cons
Acoustic	AQUATEC AQUAmodem1000 [40]	10 km	{0.1,2} kb/s		Affected by acoustic noise and multi-path
	Arctic transmission [31]	100 km	1 b/s	Proven technology	
	BaltRobotics Prototype [38]	100 m	115 kb/s	No need for LOS	High power consumption
	Benthos ATM 90 [26]	{1.5,6}	{15,2.4} kb/s	Range up to 30 km	Order-of kb/s bit rates
	Develogics HAM.NODE [30]	30 km	145 b/s	Robust in deep water	Poor in shallow waters
	EvoLogics S2C R series [27, 33, 39]	{0.35,7} km	{64,7} kb/s	vertical link	Affected by sound speed gradient
	FAU Hermes modem [35]	150 m	87.7 kb/s	Availability of good channel models for simulation purposes	High latency
	LinkQuest UWM series [41]	1.5,5 km	{5,17.8} kb/s		May impact marine life
	MIT Prototype [36]	200 m	100 kb/s		
	Northeastern SEANet [37]	10s m	{41,250} kb/s		
Sercel MATS3G [29]	{2.3,16.5} km	{16.5,0.1} kb/s			
Subnero WNC [34]	3 km	15 kb/s			
EM / RF / MI	CoSa WiFi [17]	10 cm	{10,50} Mb/s	High Bandwidth	Very short range (<10 m)
	Dalhousie Univ. Prototype [21]	10 m	8 kb/s	Low Latency	Affected by water salinity and conductivity
	CoSa EF Dipole [17]	{1,8} m	{0.2,1} Mb/s	Good performance in fresh shallow water	Few modems available
	INESC TEC Dipole [18]	1 m	1 Mb/s	Crosses air/water/seabed boundaries	Susceptible to EMI
	WFS Seatooth S200 [19]	{10,40} m	100 b/s	No need for LOS	High power MI may impact marine life
	WFS Seatooth S300 [19]	{4,10} m	{156,25} kb/s		
WFS Seatooth S500 [19]	10 cm	10 Mb/s			
Optical	Aquatec AQUAmodem Op1 [8]	1 m	80 kb/s	Mb/s bit rates	Short range (<100 m)
	ENEA PoC [9]	1 m	{0.25,2} Mb/s	High bits per Joule capacity	Affected by turbidity, marine fouling and ambient light
	Keio optical modem [10]	3 m	2 Mb/s	Good performance in clear dark water	Needs LOS and good alignment
	IST Medusa Optical Modem [11]	10m	{20,200} kb/s	Low latency	
	MIT low power led modem [12]	{6.5,8} m	{10,1} Mb/s		
	Penguin Automated Systems [13]	{10,300} m	{100,1.5} Mb/s		
	Sonardyne BlueComm 500 [14]	{7,150} m	{500,10} Mb/s		
	SPAWAR optical modem [15]	2 m	10 Gb/s		
Sant'Anna OptoCOMM [16]	{5,7} m	10 Mb/s			

Science developed a prototype for WiFi communication underwater [17], with a rate of 10-50 Mb/s up to 10 cm. The University of Applied Sciences also developed a dipole [17] antenna, to communicate with a rate of 0.2 to 1 Mb/s and a range of 1-8 m, depending on the water conditions (i.e., 1 meter in salty water, 8 meters in fresh water). On the other hand, Dalhousie University developed a MI prototype that achieves 8 kb/s at 10 m [21], to perform low-rate low-latency communications.

Unlike RF communications (which are very effective at short range and are not affected by multipath or alignment issues), optical communications are more suitable for ranges between 5 and 100 m, especially in deep dark waters. Blue and green lights, which have a wavelength of 470 and 550 nm respectively, are the most widely used for underwater optical communication. The light source can be either a laser or a matrix of light emitting diodes (LEDs). The high-power off-the-shelf Sonardyne Bluecomm modem line employs either

or both wavelengths, depending on the model [14]. Laser sources can provide a very high bandwidth and a bit rate up to 0.5 Gb/s (as is the case, e.g., for the Bluecomm 500). Still, lasers need very good alignment between the transmitter and the receiver. LED-based modems like the Bluecomm 200 offer a tradeoff in this respect, with a lower bit rate (tens of Mb/s) with much looser alignment requirements. Another commercial off-the-shelf optical modem is the AQUAmodem Op1 [8], which achieves 80 kb/s at 1 m. Although its performance is not as high as that of the Bluecomm line, it has a lower power consumption and a different application target. Customized LED-based optical modems are also developed by Penguin ASI [13, 44]; the maximum performance of their system is order-of-100 Mb/s at hundreds of meters, but comes at the price of very bulky and expensive modems that are only suitable for extremely specialized applications. Data muling applications often rely on small and cost-effective

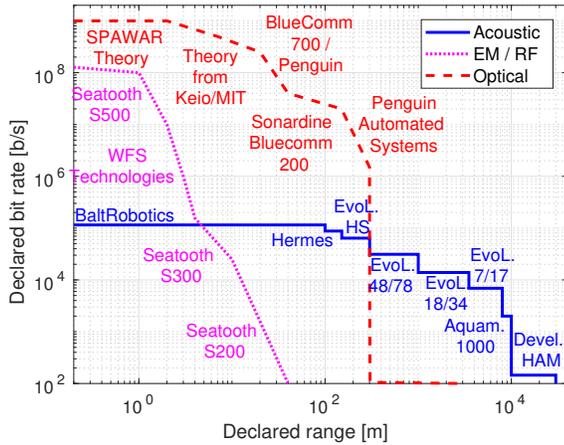


Figure 1: Nominal bit rate vs. range for the best among the mature technologies listed in Table 1.

AUV designs [45]. To reduce costs, these AUVs mount a custom optical modem for high-rate communications [9, 11, 16], rather than a commercial one.

The details of the modems presented in this subsection are summarized in Table 1. A summary of the bit rate as a function of range for current state-of-the-art optical, electromagnetic, and acoustic modems is provided in Fig. 1.

2.2 Multimodal networking

The concept of multimodal underwater communication is, in some way, akin to the deployment of multiple radio systems on board the same node in the context of terrestrial radio networks. In the underwater environment, one of the first multimodal systems was employed in [22], which presents a data muling system where an AUV equipped with acoustic communications processes the video feed of an underwater camera to align with underwater sensors, and downloads data through optical communications. Acoustic communications are employed for control, synchronization and parameter setting.

The variable-depth moored acoustic nodes presented in [23] can surface to exploit radio communication links. The system balances between the energy required for the node to reach the surface and the energy consumption of underwater acoustics, and chooses either strategy depending on data transmission requirements. The autonomous underwater exploration device presented in [46] can rely on different underwater communication capabilities. The authors discuss the tradeoffs between frequency-shift keying (FSK)-based modem technology and custom low-cost modems [47].

A notable feature of multimodal systems is that the composition of multiple powerful physical layers may not be

necessary to achieve good performance. For example, [48] considers a multimodal optical/acoustic system, where the optical part is implemented through an infrared modem assembled from inexpensive off-the-shelf components. The optical modem provides an alternative communication channel, and is shown to substantially improve the performance of underwater acoustic networks in terms of synchronization and TCP connections.

MURAO [49] is the first routing protocol to employ multimodal optical and acoustic communications. It assumes a clustered underwater network structure, where acoustic communications enable cluster formation and management, whereas intra-cluster communications are carried out using optical systems. Q-learning [50] is employed to set up and iteratively improve the routing structure and topology.

More recently, OMR [51] has been proposed as an optimal approach to convey data packets through a converge-casting network topology, in such a way that the utilization of multimodal links is highest while respecting the forwarding capabilities of intermediate relays, and while ensuring some degree of fairness to all nodes. Optimal decisions are made in a distributed fashion. The MARLIN routing protocol for underwater networks [52] relies on a reinforcement learning approach to identify the multihop routes that provide an overall minimum delay or highest degree of reliability through an underwater network. The system learns both the optimal hop sequence and which of the multiple available acoustic devices should be used by each relay.

In the hybrid optical/acoustic multimodal networks considered in [53], real-time video streaming is serviced through optical channels, whereas acoustic communications provide a feedback channel to, e.g., send acknowledgments and coordinate the alignment of optical modems. Acoustic communications also provide a fallback solution in turbid waters, where optical systems would not be able to establish reliable links. Such a hybrid solution is shown via simulations to outperform both optical and acoustic communications alone.

In [54], the author consider a mobile AUV in the spirit of [22], and propose to optimize the path of the AUV in order to maximize the value of the information retrieved from the sensor nodes, which loses value as time goes by. The AUV uses optical communications to retrieve data, whereas acoustic communications are employed to notify the AUV of new data being generated.

The efficient management of multimodal underwater links often requires to be able to automatically switch among different communication technologies using only locally available information. In the context of the wireless remote control of a remotely operated vehicle (ROV), [25, 55] provide a few policies that achieve such switching. In [56], more complex scenarios are implemented using the free-access

DESERT underwater framework [57] and evaluated in a diver cooperation scenario.

The authors in [45] propose hybrid acoustic/optical devices to be employed in the coordination of swarms of AUVs, as well as to transfer information among the members of the swarms. The custom design of both the acoustic and the optical modem is also discussed. The authors in [58] exploit a custom re-configurable underwater acoustic modem to implement a “bilingual” modem concept. Such modem switches among two available modulation schemes, namely the NATO standard JANUS [6, 7] and a higher-rate MFSK modulation format. JANUS provides a first-contact scheme and a robust fallback, whereas the MFSK scheme was used to achieve higher data rates when channel conditions so allowed.

3 CASE STUDIES

We now provide two examples of applications of multimodal communications in underwater networks, based on our prior work in [25, 51].

3.1 Multimodal remote control [25]

With the development of high-performance acoustic modems and of non-acoustic physical communication systems, a vested interest has appeared for the tele-operation of semi-autonomous AUVs or remotely operated vehicles (ROVs). While underwater wireless communications are unlikely to provide a full replacement for the umbilical control cable of an ROV, they still constitute a good opportunity to increase the range of a submerged device up to the coverage range of the used communications technologies. Wireless communications may also permit to untether the ROV, thereby increasing its agility and freedom of movement.

Still, the capability to steer the movement and actions of an ROV, its responsiveness to commands, and the feedback it can send to the operator vary with the used communication technology. In this context, multimodal communication systems offer a good opportunity to at least define a set of quality-of-control levels, each to be covered using a specific technology. For example, there can exist mandatory and optional control features. Mandatory features may include movement commands, ROV tool management and ROV feedback. Optional features may include communication-intensive services such as video streaming. While ideally all services should be supported, the optional ones can be suspended when using a low-bit rate communication link [25].

As an example, we consider the task of controlling the movement of an ROV through a closed-loop trajectory that drives the ROV up to 200 m far from the controller. The ROV is assumed to operate in deep waters, in order to make it possible to employ an optical modem connection. Additionally, the ROV is equipped with different non-interfering

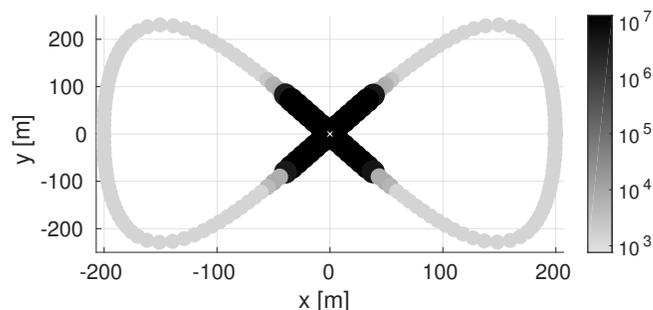


Figure 2: Throughput of the multimodal ROV control system against the position of the ROV along the considered closed-loop trajectory (expanded after [25]).

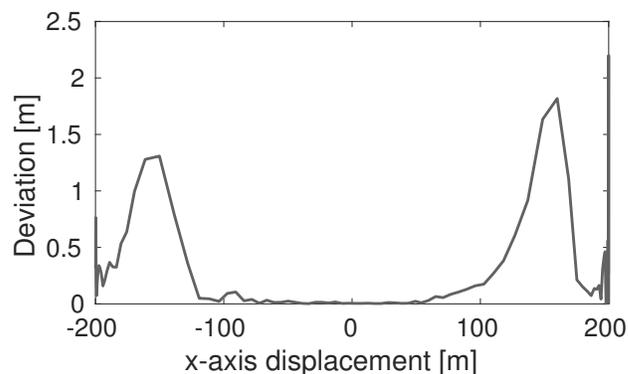


Figure 3: Deviation from the desired ROV route as a function of the position of the ROV (after [25]).

acoustic technologies, namely: an optical modem akin to the Bluecomm model, operating at a rate of 5 Mb/s within a maximum range of 90 m; a Hermes acoustic modem, operating at 87.7 kb/s within a range of 120 m; and an EvoLogics HS acoustic modem, working at 30 kb/s of useful data rate within a range of 300 m. We remark that the optical modem was not considered in [25]. We simulate this scenario using the DESERT Underwater framework [57], where we employ a TDMA scheme for medium access control. TDMA slots are assigned different sizes to accommodate the control messages (which are typically short) and the typically larger ROV feedback data feed. A physical-layer signaling mechanism is in place to promptly switch among different communication technologies. We assume deep water operations, where the total optical attenuation coefficient of the ocean is set to $c = 0.033 \text{ m}^{-1}$.

In Fig. 2 we show a view of the ROV trajectory from above, where the trajectory is colored with a different grey shade depending on the bit rate achieved over that specific link. We observe that the control system switches through the different technologies of the multimodal system to take advantage of the best available communication links. In particular, within about 90 m from the controller, the ROV exploits

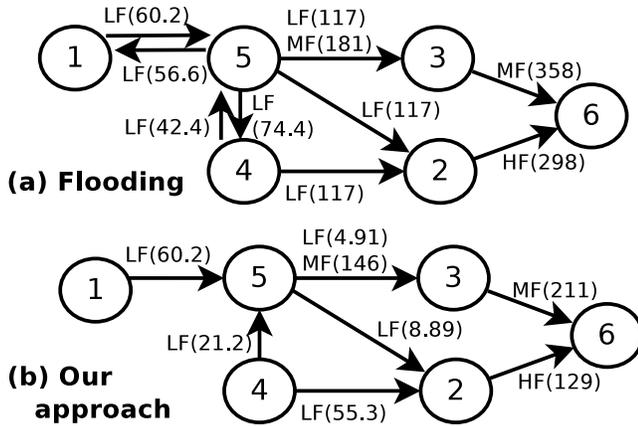


Figure 4: Illustration of the operation of multimodal routing for (a) flooding, and (b) our routing solution. Graph edges show the total number of bytes transmitted over that edge needed in order to successfully deliver the same packets to the sink (after [51]).

an optical link for very high speed communications, and progressively switches to lower bit rate and longer-range acoustic transceivers as the distance increases. The Hermes modem is exploited roughly within 90 and 120 m of distance, whereas the EvoLogics modem covers the remaining part of the trajectory. Under the assumptions that steering commands are given once every 7 s, Fig. 3 measures the expected deviation from the desired AUV trajectory. These deviations are typically due to technology switching delays and possible errors in the forward or feedback links. The maximum path deviation is less than 2 m, which suggests that the switching system effectively chooses the optimal technology at any given distance.

3.2 Optimal multimodal routing [51]

One of the main impacts of multimodal technologies comes into effect in the setting of a sensor network. Here, each node may have a single or multiple ways of communicating, and the challenge is how to efficiently propagate packets within the multimodal network. In this case study, we consider a setup with a meshed network with no pre-defined routing paths. The aim is to pass packets over multiple hops from any source to a single sink while minimizing the end-to-end transmission delay and maximizing the network throughput. The solution is found by determining the communication technologies to be used at each hop, and the amount of data to be transferred. For a given hop distance, the simplest approach would be to choose the technology with the highest capacity (e.g., [49]). However, for high network traffic, this approach can generate bottlenecks. Alternatively, performing routing using all available communication technologies,

i.e., through a flooding approach, generates significant overhead and is much more prone to collisions.

In [51] (see also [59] for an extended version), we have described a distributed multimodal routing solution that only assumes knowledge of the communication capacities of one-hop nodes. The solution tries to fully exploit all the available communication links between a node and its neighbors, while avoiding routing cycles. Bottlenecks are avoided by allowing nodes to communicate the status of their current buffers, and by imposing a fair distribution of relayed traffic such that nodes with multiple paths to their destinations are expected to spread their traffic. To that end, the routing algorithm works by solving a constrained linear optimization problem before the transmission of each packet. The utility function maximizes the throughput, while the constraints ensure that capacity limitations are met, distributed fairness is achieved, and all packets are served.

In Fig. 4, we illustrate the operation of our routing solution. The considered scenario includes three types of underwater acoustic communication technologies: low-rate, long-range, low-frequency (LF); mid-rate, mid-range, mid-frequency (MF); and high-rate, short-range, high-frequency (HF). The network includes six nodes, each of which has at least the LF technology, and at random also MF, HF, or both. The arrows in the figure are labeled according to the number of bytes transmitted over the corresponding link in order to convey the same packets to the sink (node 6). Compared to flooding (Fig. 4a), our algorithm (Fig. 4b) requires the transmission of a significantly lower number of bytes, and produces a more balanced traffic distribution. In addition, Monte-Carlo simulations employing 1000 different network topologies show that the delivery ratio of our approach (>60%) is even higher than the delivery ratio of flooding (55%) despite the large amount of redundancy generated by the latter.

4 CONCLUSIONS AND OUTLOOK

Multimodal communications are currently regarded as a feasible solution to satisfy the performance requirements of complex telemetry and networking scenarios. The research on multimodal systems and networks has been taking momentum, and currently has the objective to provide high-performance communications beyond the limits of the typical bit rate vs. coverage vs. power consumption tradeoffs offered by a single-technology communication system.

It is believed that several applications will benefit from multimodal communications in the future: this includes, among others, optimal AUV trajectory design strategies; general-purpose underwater sensing and monitoring scenarios, where the submerged equipment will be able to convey more data per unit time to the sink with less energy; and

high-performance point-to-point links as encountered in remote control applications. The latter represent an interesting case study for the marine industry at large [60], due to the increasing interest in the proper exploitation of underwater mineral and hydrocarbon resources, and in the consequent interest of marine preservation authorities to monitor such activities to ensure wildlife preservation [61].

While Mb/s bit rates are currently achieved only by optical communications at close distance, there are a number of acoustic systems currently being researched or entering their prototype stage, that also offer order-of 100 kb/s bit rates at very close distance. This is often enough even for low-rate video applications [25], and thus constitutes a promising research direction. It is also worth emphasizing that fully acoustic multi-modal communication systems may be facilitated in the future by the recent thrust towards general-purpose, reprogrammable open modem architectures [1]. In this case, the modem control system could be centralized, and the multimodal device would only need to differentiate its transducers, rather than having to physically incorporate different modems.

More complex systems encompassing different physical layer technologies e.g., acoustics and optics, will initially be limited to niche or specific applications, such as fast on-site data upload/exchange, as well as for the remote control of complex equipment. This is due to the engineering effort required to integrate different systems, the higher energy consumption that this requires, the high cost of optical modems, as well as the lack of off-the-shelf solutions for RF and MI modems. A decrease of optical modem prices, or the improvement of RF and MI modem designs to a stage that offers reliable communications at proven data rates within a predictable communication range will facilitate the integration of such modems into future multimodal systems.

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