Hybrid Infrastructure for Autonomous Underwater Operations

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Abstract

Coordinated sampling via autonomous underwater vehicles (AUVs) is a major trend in ocean monitoring and exploration. However, the current underwater communication and networking technologies are still primitive, as they cannot provide the needed reliability and data rates for the navigating AUVs. As the main means for information exchange, underwater acoustic communications suffer from limited bandwidth and large propagation delay. We propose a hybrid network infrastructure to support communications and networking among multiple AUVs. As an alternative to direct AUV-AUV acoustic communications, the hybrid architecture uses autonomous surface vehicles (ASVs) that are connected by the radio-frequency (RF) wireless links as a high data rate backbone above the sea surface. At the same time, ASVs serve as mobile acoustic base stations to meet the communication needs of the navigating AUVs. This architecture uses a fleet of ASVs to increase the achievable network throughput and to reduce latency. In this chapter, we study the integration of short range acoustic communications with long distance RF wireless communications. Through extensive simulations using the ns-3 network simulator, we compare network throughput and end-to-end delay of different scenarios between hybrid and pure acoustic networks.

1 Introduction

The oceans cover more than 70% of the surface of our planet, forming one of the most critical physical systems to life. To support ocean monitoring and exploration missions, the prevailing strategies have been to use either seafloor fiber-optic cables, e.g., ocean observatories around the globe [13, 26, 28, 29], or satellite-linked stationary in-water moorings [5] as backbones for communications and networking. The sea-floor observatories often have enormous price tags for development and maintenance. Further, the seafloor infrastructures are inflexible to relocate or to accommodate evolving societal needs, although supporting invaluable long-term ocean observations. In addition, although a dense array of satellite-linked stationary moorings may cover a relatively large area, this static solution results in high costs as well as operational difficulties for deployment and recovery.

In recent decades, autonomous underwater vehicles (AUVs) (including underwater gliders) have emerged as effective and versatile tools to respond to vital needs in the oceans, lakes, and estuaries [45]. Successful applications enabled by AUVs include, just to name a few, adaptive environmental monitoring, geological surveys, ocean observations, and national defense. In these applications, AUVs may gather orders of magnitude more measurements than the traditional ship-based surveys, at much lower cost and/or in hazardous conditions (e.g., underwater during hurricanes). In addition, the ability to retrieve imagery and scientific data from AUVs via a communication network will greatly enhance human-vehicle interactions and real-time decision making [10], thus supporting critical real-time underwater missions, *e.g.*, disaster responses.

Fleets of coordinated AUVs operating together facilitate applications of distributed sampling and exploration [33], including 1) tracking marine life to understand the life cycles of sharks, jellyfish, lobsters, etc. [34]; 2) monitoring and tracking fast-evolving plumes, algae, or other fast-evolving features [31]; 3) mine detection and other national defense applications [25]. In addition, several trends have driven the needs to establish motion coordination and team behaviors [22, 23]. For instance, distributed real-time measurements are critical to sparse sampling in vast oceans or Great Lakes. Coordinated AUV-fleets are poised to perform sophisticated missions in highly dynamic oceans, and AUV-fleets can greatly reduce the sensory and capability requirements on individual members, thus reducing the overall mission cost.

These applications all demand reliable communication and networking among the participating AUVs, and between AUVs and their external monitoring, control, and human decision making. However, it is well known that wireless communications in the underwater realm is an intractable challenge. In field operations, scientists have been adopting the concepts of delay-tolerant networking to cope with intermittent underwater communications [32]. In such context, *encounters* are used as the main opportunities to communicate.

When considering underwater wireless communications over ranges beyond tens of meters, acoustic communications should be used, because both electro-magnetic and optical waves suffer strong attenuation in the aquatic environment. At the same time, the unique characteristics of acoustics further challenge underwater communications. The fundamental difficulty lies in the limited bandwidth, with a maximum of only tens of kilohertz. In addition, due to the highly dynamic

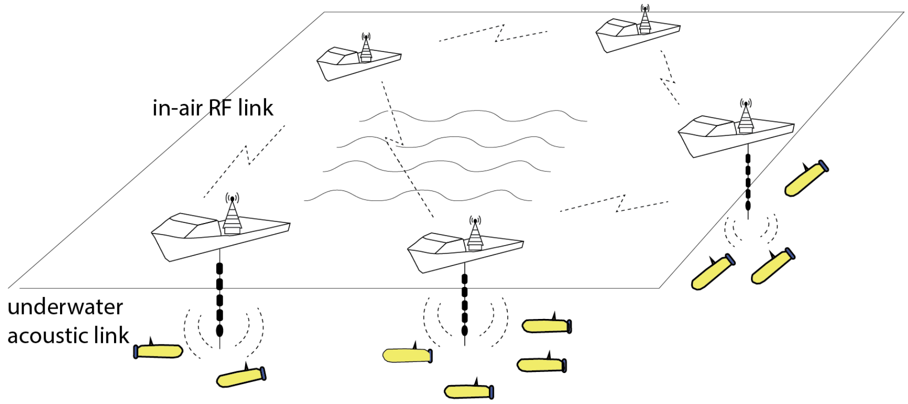


Figure 1: Scenario of hybrid RF-acoustic networking and ASV navigation.

ocean environment, the acoustic communication channel suffers large dispersion in both time and frequency domains (i.e., time-varying multipath), constraining spectral efficiency. Further, underwater sound speed, 1500 m/s, is five orders of magnitude slower than that of electromagnetic waves in air. The resulting long propagation delay introduces spatio-temporal uncertainty [40], which seriously limits the efficiency of networking protocols.

The mobility of AUV-fleets introduces additional challenges. First, AUVs often experience high uncertainties in localization and time synchronization, due to the lack of GPS signals underwater. Second, AUVs may be sparsely deployed over a large aquatic region, so that network connectivity becomes intermittent. Third, the network topology of a fleet of AUVs is in constant change, leading to variable and long propagation delay. Mobility also creates variation on data rates in different geographical locations of the network, as the achievable data rate decreases with the increase of communication range.

We propose to use low-cost autonomous surface vehicles (ASVs) equipped with both acoustic and RF modems to support underwater missions, as depicted in Fig. 1. The ASVs form a connected and adaptive backbone via RF links above the water surface while connecting AUVs via underwater acoustic links. The connected backbone is maintained by a swarming-based ASV navigation strategy for enhanced data rates and much reduced end-to-end latency.

Fig. 2 illustrates the functional architecture of the proposed mission-defined hybrid infrastructure, which 1) directly addresses the communication and network challenges and 2) allows seamless integration with autonomy and control. The hybrid infrastructure complements existing AUV autonomy middleware and behavior architecture, such as MOOS-IvP [27], and tri-level hybrid control architecture of mission planning and executive [39], as an efficient and reliable communication infrastructure among AUVs. Using the defined mission from mission planning as inputs, the ASV-based

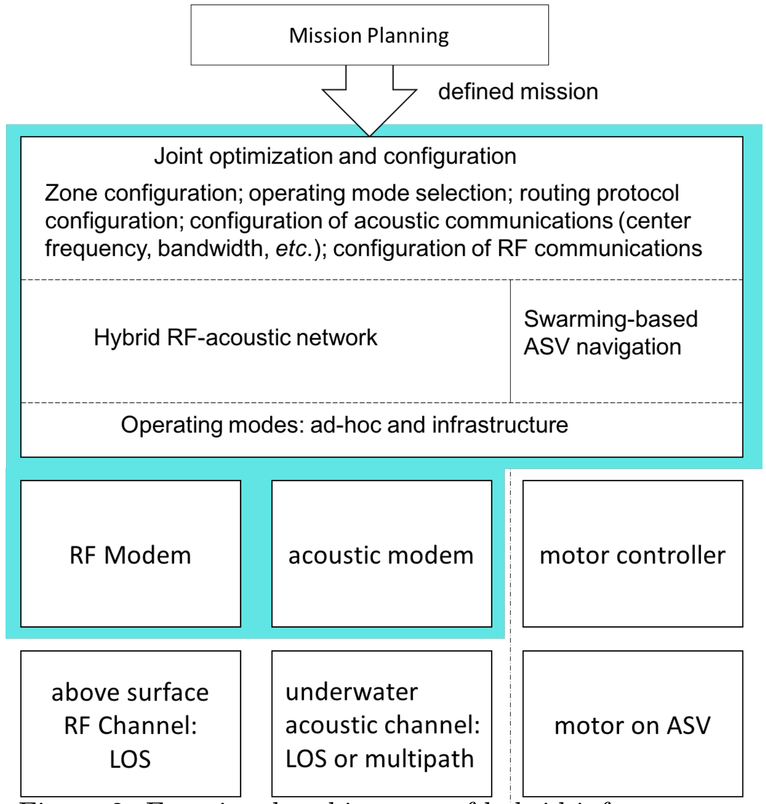


Figure 2: Functional architecture of hybrid infrastructure.

hybrid RF-acoustic infrastructure facilitates networking among AUVs and to the outside world by *optimizing* the navigation of ASVs to *jointly* (1) trail respective AUVs to maintain short range and close to 'vertical' acoustic links for improved data rates, reduced propagation delay, and enhanced reliability, and (2) form an adaptive and connected RF 'backbone' above water surface to support high data rate and reliable communications. The hybrid short range underwater acoustic links and low-latency in-air RF links create much improved network throughput, efficiency, and reliability. To sustain a connected ASV backbone, AUVs may be instructed not to move away from associated ASVs so as to be connected with other AUVs within the same mission.

Such a hybrid networking infrastructure represents a new network, where two communication constituents differ greatly in their data rates, link performance dynamics, power efficiency, and network coverage. Further, the five order of magnitude difference in wave propagation speed leads to large disparity in network latency between subsurface and in-air sub-networks. One critical issue is to guarantee reliable connectivity among AUVs through navigation of ASVs, in the presence of aquatic dynamics (ocean currents, surface waves) and location uncertainty of AUVs.

The chapter proceeds to review related work in Section 2. Hybrid RF-acoustic networking among AUVs via ASVs is introduced in Section 3. Swarming-based ASV Navigation is briefly described in

Section 4. Parameters used for the simulation along with Simulation results of hybrid RF-acoustic communications between AUVs are presented in Section 5. Section 6 summarizes this chapter with future research directions.

2 Related Work

It is well recognized that acoustic communications alone can not meet the needs of data telemetry in underwater missions. To address the issues, a number of hybrid schemes have been proposed: acoustics combined with fiber-optic cabled sea-floor stations (OOI projects), acoustics with satellite links, and RF-acoustic method that is used in a centralized network to collect sensory information of underwater nodes and to control them.

Mobility of AUVs has been used to assist routing among drifting sensors [18, 20, 44] or in data muling and encounter-based connectivity [21, 35]. Some of these schemes used only acoustic communications [8], while others used a combination of optical and acoustic methods for communications [42].

ASVs are low-cost, easy-to-operate, and versatile platforms [4, 24, 38]. Being on the surface, ASVs have several advantages: 1) access to GPS and RF communications [4], 2) more cargo space and possible long endurance in the ocean, 3) access to solar energy [16] and different propulsion solutions. In addition, ASVs can continuously provide GPS information to assist AUVs with more accurate and precise localization [2, 14, 43].

The use of ASVs has also been reported in various scientific field experiment efforts since 2000, for example in cooperative marine autonomy [9], ocean remote sensing [12], and hydrographic survey. [1]. As reported in [11, 30, 41], *individual* ASVs were used as communication gateways for underwater platforms. A single semi-submersible ASV was used to support AUV communication and positioning [36]. Large scale experiments in [3, 37] also reported the use of individual ASVs as communication gateways to control centers or satellites. *To our best knowledge, there are no reported efforts on using multiple ASVs to form a hybrid network or even an RF network above the sea surface.*

As a communication platform, although ASVs face several challenges, solutions exist. First, the stability of these ASVs are subject to the dynamics of surface waves. Therefore, they are more suitable to operate in relatively calm sea water surfaces. One solution is to use semi-submersibles. Second, close to the surface, the acoustic receiving array may not have good reception when the ocean is downward-refracting for acoustic waves. One solution is to use relatively long cables for reception as well as transmission. Third, the RF modems above the water surface often rely on line-of-sight (LOS) for reliable communications. To cover large areas, ASVs need to install elevated RF antennas which can be accomplished with bigger vessels.

3 Hybrid RF-Acoustic Networking among AUVs via ASVs

The proposed hybrid infrastructure consists of two complementary components: hybrid RF-acoustic networking of ASVs and AUVs and swarming-based ASV navigation. The benefits of hybrid RF-acoustic networking can be illustrated by the simple scenario depicted in Fig. 3, where two AUVs, separated by some distance apart, navigate collaboratively to sample the ocean. Using conventional schemes, the two AUVs communicate via the direct acoustic link over a *horizontal* channel. Due to the slow underwater sound speed, the communication latency is high. In addition, due to the long distance between the two AUVs, the acoustic link can only support lower data rates with limited reliability subject to multipath and ocean fluctuations.

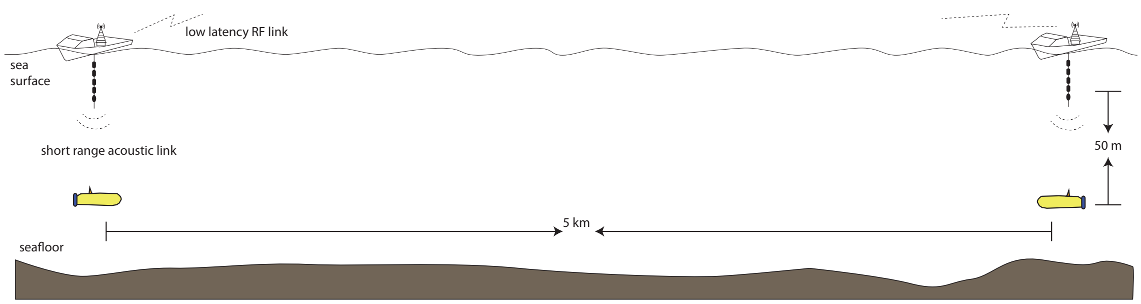


Figure 3: Simple scenario of hybrid RF-acoustic networking.

In contrast to a single long delay, unreliable acoustic link, the central idea of hybrid RF-acoustic networking is to use ASVs to *trail* AUVs by a short distance so as to bridge the two short range underwater acoustic communications (between two pairs of AUV and ASV) with high speed, low latency RF communications (between the two ASVs above the sea surface). Having short range underwater acoustic communications between a pair of AUV and ASV not only reduces the latency of acoustic communications, but also makes the acoustic communications closer to *vertical* to mitigate refraction[1] and multipath. Overall, end-to-end communications between two AUVs over a hybrid RF-acoustic network achieve lower latency, higher bandwidth, and improved reliability.

Fig. 4 compares the latency of transmitting one data packet between the two AUVs in Fig. 3. In

[1]Because water is much more stratified in the vertical than the horizontal.

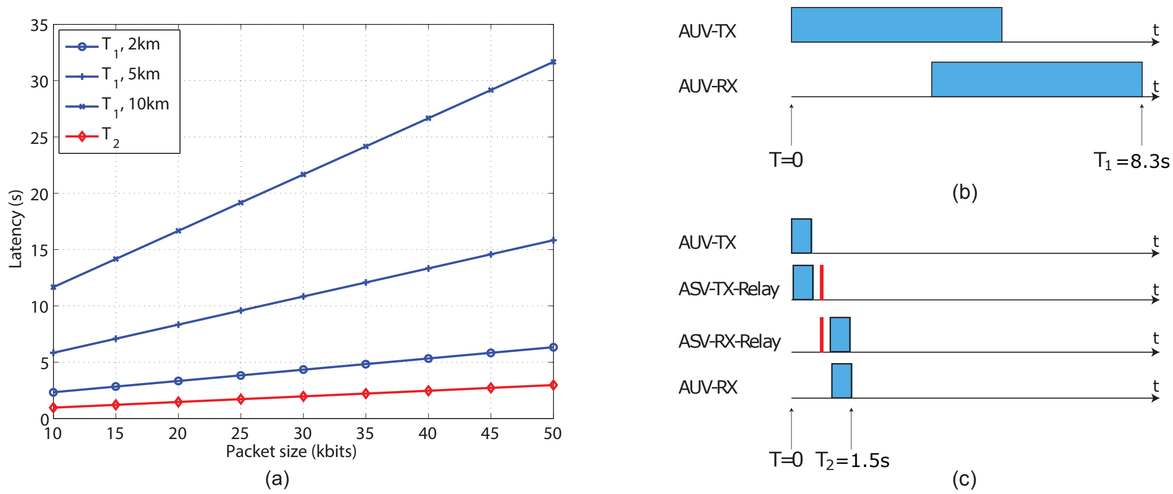


Figure 4: (a) Comparison of packet delivery latency between the traditional and proposed schemes for different AUV-AUV ranges. Timing diagram comparison between the traditional scheme, shown in (b), and our hybrid scheme, shown in (c), for $W = 20$ kilobits and $D_{HA} = 5$ km. In (b), $T_1 = 8.3$ sec while $T_2 = 1.5$ sec in (c).

this illustrative comparison, the data packet has W kbits. The two AUVs are separated by distance D_{HA} ranging from 2 km to 10 km. Distance D_{VA} between an AUV and its trailing ASV is 50 m. Underwater sound speed c_A is 1500 m/s. It is commonly believed that the achievable data rate R_{HA} over a horizontal acoustic channel decreases with the increase of communication distance, so that the achievable *rate-range product* is a constant, say K kbps $\times$ km (*i.e.*, $R_{HA} \cdot D_{HA} = K$). Over the vertical acoustic channel, the data rate is largely limited by the available bandwidth. Based on these two principles, we assume that the rate-range product $R_{HA} \cdot D_{HA}$ is 20 kbps $\times$ km for the direct horizontal acoustic link between the two AUVs. We assume that the vertical acoustic channel supports data rate R_{VA} of 40 kbps. These data rates are realistic and have been demonstrated via different commercial products. Using the traditional schemes, the latency associated with packet delivery is $T_1 \simeq \frac{W}{R_{HA}} + \frac{D_{HA}}{c_A}$.

Using the hybrid scheme, the same data packet traverses two (short-range) acoustic links and one (long-range) RF link, and ASVs need to translate the data packet between the acoustic and RF links. We assume there is a delay, T_δ, associated with such translations. We assign $T_\delta = 0.2$ sec to allow the conversion between acoustic and RF signals and the forwarding decisions for data packets across the two constituent networks. The RF link, with a propagation speed of $c_{EM} = 3 \cdot 10^8$ m/s, can support much higher data rates than the acoustic links, for example 500 to 800 kbps. Therefore, not only is RF link's propagation latency negligible when compared with that of acoustic links, but

RF link's packet transmission latency is also very small (T_ϵ). Therefore, the packet delivery latency in the hybrid scheme is $T_2 \simeq 2\left(\frac{W}{R_{VA}} + \frac{D_{VA}}{c_A} + T_\delta\right) + T_\epsilon$.

For different communication ranges (i.e., is the AUV-to-AUV distance), latency does not vary in the hybrid scheme, where the RF link is used to address the range above the surface. In the traditional pure acoustic solution, the communication range matters in two ways. First, it increases the acoustic propagation delay. Second, the range reduces the allowable acoustic data rates. At a 2 km range, the traditional scheme uses 50 to 100 percent of extra time to deliver the same packet, compared with the proposed scheme. When the range increases to 5 or 10 km, the advantage of hybrid scheme becomes significant. The traditional scheme uses about 5.8 and 11.6 sec to deliver a 10 kilobit packet at 5 and 10 km, which are 3.7 and 7.4 folds of the latency in the hybrid scheme, respectively. Timing diagrams for transmission of a data packet of $W = 20$ kilobits are shown in Figs. 4(b) and (c) for direct and hybrid schemes, respectively. The latency values in the direct AUV-AUV link and the hybrid network are $T_1 = 8.3$ and $T_2 = 1.5$ sec, respectively.

When the packet size increases, the traditional scheme lags even more behind than the hybrid scheme. We neglect the PHY receiver decoding delay, which is often small compared with packet duration. If we take into account the link reliability, we will see further advantage of the hybrid scheme. The short-range acoustic links are much more reliable than the long-range horizontal acoustic link, especially in the dynamic ocean environment. Often in the traditional scheme, high packet loss in the long horizontal channels leads to excessive re-transmission and even network failure. Furthermore, in the hybrid scheme, there are two segments of short-range acoustic links in the end-to-end path between two AUVs, which may be far apart to form two different contention domains so that respective acoustic transmissions do not interfere with each other. This allows concurrent acoustic transmissions to further reduce packet delivery latency.

4 Swarming-based ASV Navigation

Given a defined mission for AUVs (such as waypoints, destination, etc.), the hybrid infrastructure is to navigate ASVs by jointly (1) trailing respective AUVs to maintain local acoustic links, and (2) forming a connected and adaptive RF backbone to support inter-AUV communications. However, given the dynamic nature of the aquatic environment (current, wind, etc.), a fully decentralized scheme is deemed necessary to 'coordinate' the navigation of ASVs so that all the AUVs move toward the common goal to complete the defined mission, stay connected during the mission, and avoid potential collision. To accomplish this objective, we propose *swarming-based ASV navigation* based on the three-zone swarming model [6].

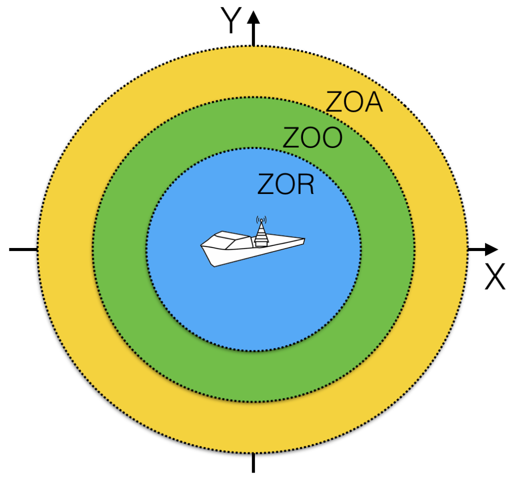


Figure 5: Three-zone ASV swarming model

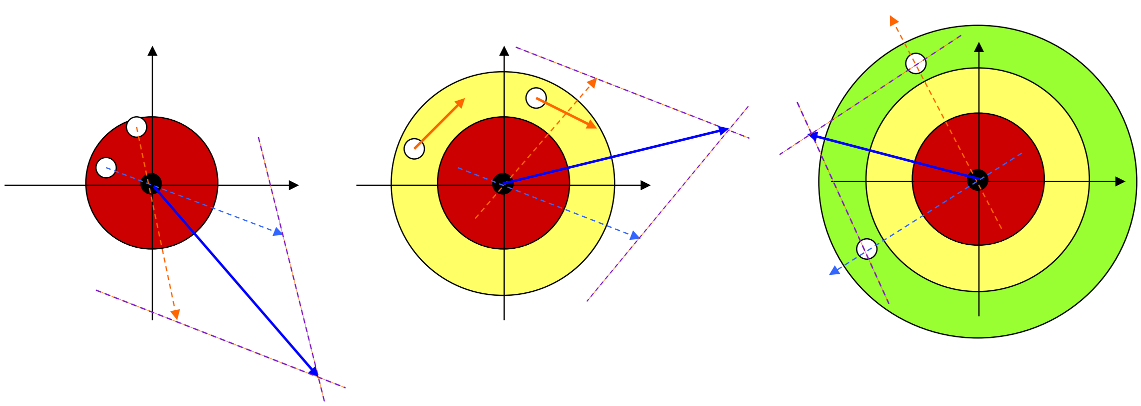


Figure 6: Move away, move along, and move towards

In general, swarming is a collective behavior exhibited by entities, particularly animals, of similar size which aggregate together, perhaps milling about the same spot or perhaps moving *en masse* or migrating in some direction. Swarming is typically defined by a set of rules which a group of nodes follow to interact *locally* with other proximal nodes without any centralized control.

In ASV swarming, the perceptual field of each ASV, as defined by its RF communication range, is divided into zone of repulsion (ZOR), zone of orientation (ZOO) and zone of attraction (ZOA), as depicted in Fig. 5. Given a distribution of N ASVs, to coordinate with neighboring ASVs in different zones, an ASV will move *away* from its neighboring ASVs in ZOR or move *along* with its neighboring ASVs in ZOO while moving *towards* its neighboring ASVs in ZOA, as depicted in Fig. 6.

Let ASV i be located at position vector P_i and pointing in direction D_i. We define three decision vectors,

$$DR_i = \sum_{j \in \mathrm{S_{ZOR}}} \frac{R_{ij}}{|R_{ij}|} \qquad DO_i = \sum_{j \in \mathrm{S_{ZOO}}} \frac{D_j}{|D_j|} \qquad DA_i = \sum_{j \in \mathrm{S_{ZOA}}} \frac{R_{ji}}{|R_{ji}|} \tag{1}$$

where $R_{ij} = P_i - P_j$ is a displacement vector between ASV i and ASV j, and S_{ZOR}, S_{ZOO} and S_{ZOA} are the sets of indices of ASVs in the zones of repulsion, orientation and attraction, respectively.

Let $|\mathrm{S_Z}|$ denote the number of ASVs in zone Z. Assuming that decision vectors are normalized as unit vectors, a generic ASV swarming algorithm can be summarized as follows.

1. If $|\mathrm{S_{ZOR}}| \neq 0$ then $V_i = DR_i$, Break;
2. If $|\mathrm{S_{ZOO}}| \neq 0$ and $|\mathrm{S_{ZOA}}| = 0$ then $V_i = DO_i/|DO_i|$, Break;
3. If $|\mathrm{S_{ZOO}}| = 0$ and $|\mathrm{S_{ZOA}}| \neq 0$ then $V_i = DA_i/|DA_i|$, Break;
4. If $|\mathrm{S_{ZOO}}| \neq 0$ and $|\mathrm{S_{ZOA}}| \neq 0$ then $V_i = \alpha \times DO_i/|DO_i| + (1-\alpha) \times DA_i/|DA_i|$,

where α is an optimization variable between 0 and 1. Changing the relative sizes of the zones in this model resulted in different swarming behavior [7], e.g., milling or migrating in some direction. In the context of swarming-based ASV navigation, defined mission, such as desired destination, represents extra information. In this case, let $F_i = P_d - P_i$ point to the desired destination, where P_d is the position vector of the desired destination. Each ASV i then sets its new orientation to be $D_i = \beta \times V_i + (1-\beta) \times F_i$, where β is another optimization variable between 0 and 1.

5 Evaluation of Hybrid AUV-AUV Communications

We simulate different scenarios in the ns-3 simulator, where underwater acoustic network modules are available. To create hybrid network simulations, we integrate multiple components of acoustic and RF networks (PHY and MAC layers, Channel models, and Net Devices) on ns-3 node objects. On the ASV nodes, we install the Internet stack that is used by both acoustic and RF networks. The detailed hybrid network structure in ns-3 is depicted in Fig. 7. In the hybrid method, application packets of source AUV are encapsulated in the UDP protocol, sent to its associated ASV, routed to the destination AUV's associated ASV and finally received by the destination AUV. Since each source ASV knows the IP address of destination ASV in order to successfully route the packets, we

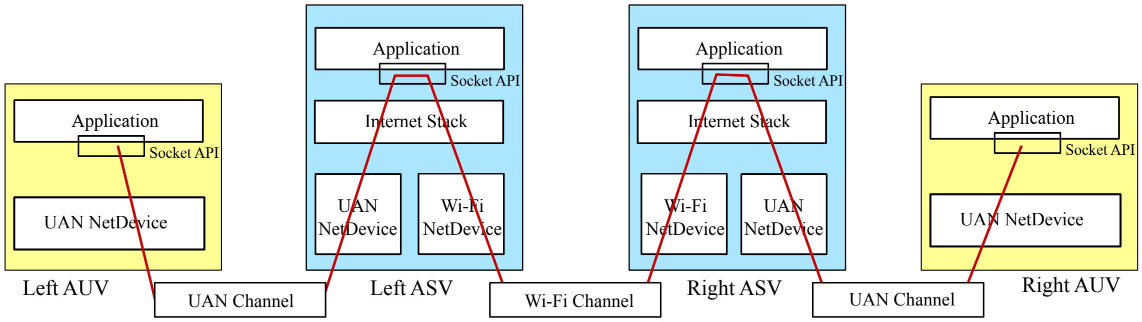


Figure 7: Simulation model of Fig. 3 in ns-3

Table 1: Parameters for the simulations

Parameter	**Direct AUV-AUV**	**Hybrid AUV-AUV**
PHY Rate (sps)	4000	40000
Data Rate (kbps)	range-rate product(20 $km \times kbps$)	40, 800
Packet Size (Bytes)	500, 1000, 1500, 2000	500,1000,1500,2000
Center Frequency(kHz)	12	200
TX Power(dB re 1 muPa)	187	177
Acoustic Model	Thorp	Thorp
Simulation Stop Time (s)	400	400

use a mapping class at each ASV to transform the IP address of destination AUV to its associated ASV, and vice versa.

Parameters used for simulations are depicted in Table 1. In all simulations, since the traffic load of RF links is less than that of acoustic links, we use the RTS/CTS mechanism to reserve the channel. In the hybrid scheme, the data rate is 40 kbps for the acoustic link and 800 kbps for the RF link [15], the AUV transmission power level is 177 dB re 1 muPa, the acoustic carrier frequency is 200 kHz, and the symbol rate is 40 kHz. In direct acoustic AUV-AUV communications, the AUV transmission power level is 187 dB re 1 muPa, the acoustic carrier frequency is 12 kHz, and the symbol rate is 4 kHz. In both schemes for the acoustic links, BPSK modulation is used. An acoustic attenuation model, the Thorp approximation in ns-3, is used [19] to characterize the pathloss. Therefore, multipath is not simulated for either of the schemes. We simulated four packet sizes varying between 500 and 2000 bytes. We assume an oracle to compute optimal intervals for traffic generations. Packet generation rate has an inverse relationship with the next packet transmission (Next TX) time. In other words, a higher packet generation rate leads to a shorter transmission interval, which is computed by the following formula:

$$\text{Next TX} = \text{PacketSize}(bit)/\text{PacketGenerationRate} \tag{2}$$

Throughput is computed as total received bits divided by the time it takes from transmission of the first packet (by a sending AUV) to reception of the last packet (by a receiving AUV). Simulations are chosen to assess the maximum achievable throughput (at the application layer) for a single AUV per each AUV-ASV pair in the hybrid Acoustic-RF and cross layer MAC-Routing protocols. Hence, to build a collision-free schedule, the Aloha MAC protocol is used in the simulations. Our simulation results show that higher throughputs are achieved with the hybrid method, which also remain intact even with increasing distance. As an example, for two AUVs located 5 km apart, and transmitting packet sizes of 2 kB, direct acoustic link achieves a maximum one-way throughput of 3960.6 bps. In contrast, the hybrid network achieves a maximum of 39847.5 bps, ten folds of the direct acoustic link's maximum throughput. Further, the end-to-end delay between two AUVs (5 km away from each other) is 0.1 second in the ns-3 simulations for the hybrid network. The delay includes both propagation delay and PHY/MAC algorithm processing delay (T_δ is not added). In comparison, the delay is 3.53 seconds in direct acoustic AUV-AUV communications.

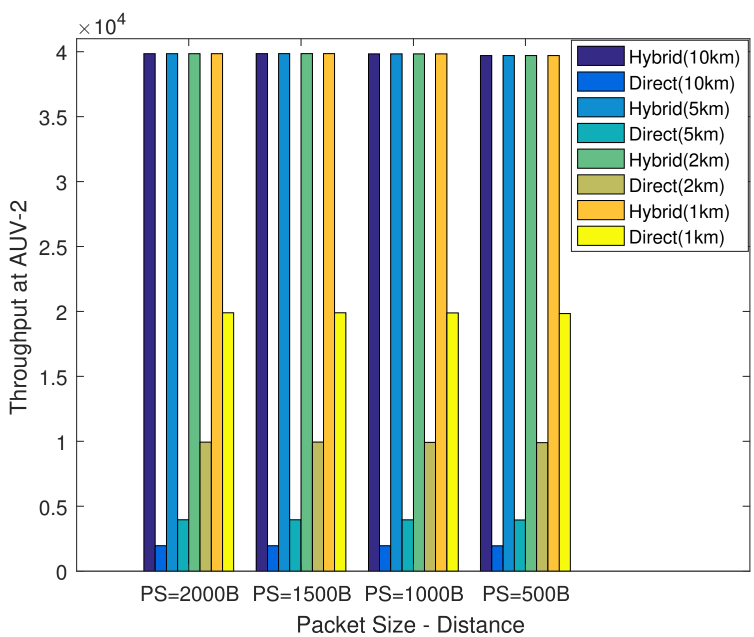


Figure 8: Packet Size (PS) *vs.* Throughput for one-way flow from AUV-1 to AUV-2 using hybrid RF-acoustic and direct method (only acoustic). Throughput is computed at AUV-2

We choose three scenarios to simulate in ns-3 with variable AUV-AUV distances of 1, 2, 5 and 10 km. The first scenario simulates one-way and two-way (bidirectional) communications among two AUVs. The second scenario simulates a network of four AUV nodes with four application flows running on them. The third scenario simulates underwater infrastructure-based networks.

Each scenario compares the achieved throughputs between the hybrid and direct methods. Variable packet sizes and different distances are examined.

5.1 First Scenario: One-way and bidirectional AUV-AUV communications

The deployment scenario is shown in Fig. 3. Results for one-way application from AUV-1 (left) to AUV-2 (right) are shown in Fig. 8, where four clusters of bars denoting throughput for different packet sizes (PS). Each cluster has eight thin bars for four different distances of the hybrid and direct schemes. In the hybrid scheme, with 40 kbps AUV-ASV link data rate, the throughput obtained is not affected by the packet size or AUV-AUV distance, because of contention-free in the acoustic and RF domains. Thus we observe a throughput of 40 kbps. In the direct scheme, the acoustic link data rate is computed from the range-rate product of 20 $kbps \times km$, *that is* 20 kbps at 1km distance. Thus, this results in higher data rate (hence throughput) for closer AUVs. The throughput for the direct one-way application flow from AUV-1 to AUV-2 is also unaffected by the packet size in the direct scheme.

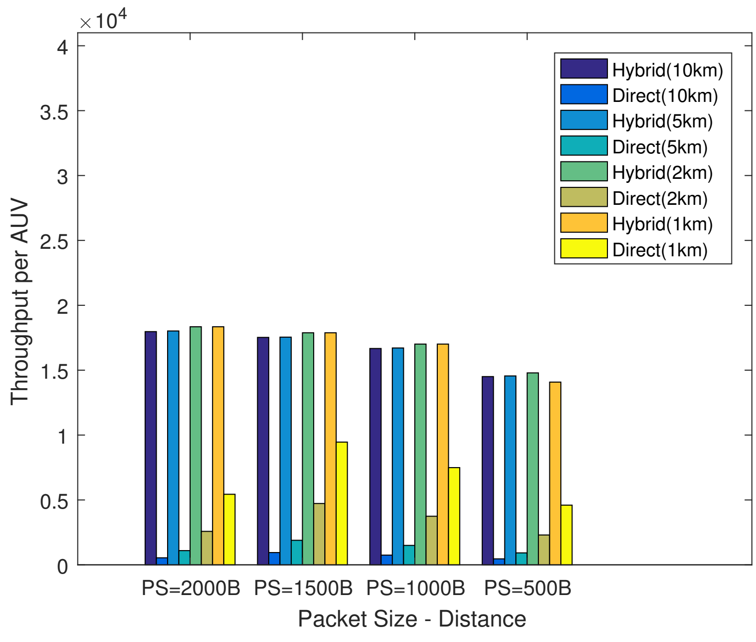


Figure 9: Packet Size vs. bidirectional throughput for two application flows between the two AUVs in the hybrid and direct scheme.

Throughput results in bidirectional hybrid/direct AUV-AUV communications for variable distances/packet sizes are shown in Fig. 9. In the direct scheme, if the application start times for both AUV1 and AUV2 are the same, the packet size of 2 kB cannot be used. This is due to TX-RX interference since in half-duplex communications, a node cannot send and receive at the same time using the same frequency. When the data rate is 2 kbps (in the case of 10 km AUV-AUV distance), 8-second packet transmission delay and 6.6-second propagation delay cause a collision and packet loss. To transmit packets of a 2 kB size, packet scheduling is used in which an AUV transmits right after reception of a packet. For other packet sizes, no scheduling is used.

We notice from Fig. 9 that the aggregated throughput of the network is on average 10% lower than one-way results for packet size of 2 kB and 30% for packet size of 500 B. Since we use no pipelining and packet generation is interval-based, larger packets are preferred. For example, PS=1500 B reaches throughput of 10 kbps per AUV. If we use pipelining and scheduling for other packet sizes (not presented in this chapter), the attainable throughput reaches half of the acoustic link data rate for each AUV. In the hybrid method, with the increase in the number of packets when smaller packet sizes are used, collision probability of RF transmissions also increases. This is due to more transmissions of control packets to reserve the channel, and, hence, larger packet sizes are preferred.

In the simulations of direct scheme and bidirectional communications, except for the packet size of 2 kB, no scheduling is used. Further, in the RF domain, both ASVs send and receive packets, which limits the achievable throughput. In the second scenario, we relax this constraint by four one-way flows in a network of 4 AUVs along with an optimal scheduler [17].

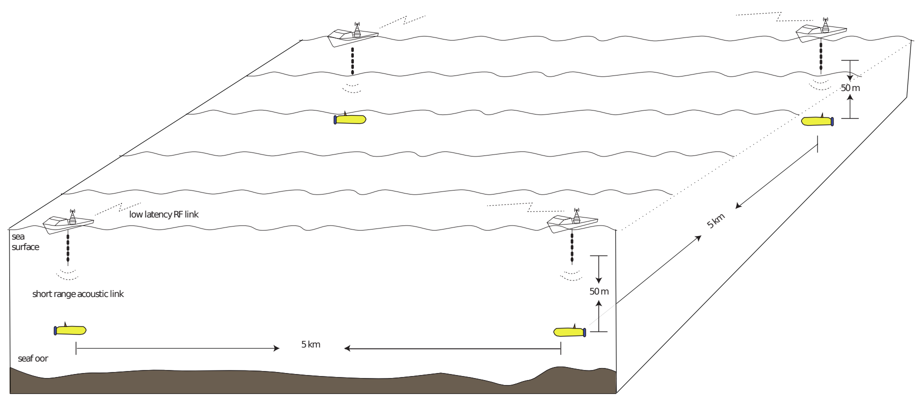


Figure 10: Network of four AUVs.

5.2 Second Scenario: Network of four nodes with four application flows

This scenario has four ASV-AUV pairs located at the edges of D_{HA} by D_{HA} grid as shown in Fig. 10. There are two flows from AUV-1 to AUV-2 and from AUV-3 to AUV-4 on the sides of the grid. There are two diagonal flows from AUV-1 to AUV-4 and AUV-3 to AUV-2. In direct AUV-AUV communications, packets of the diagonal flows traverse longer distance $\sqrt{2} \cdot D_{HA}$, and, therefore,

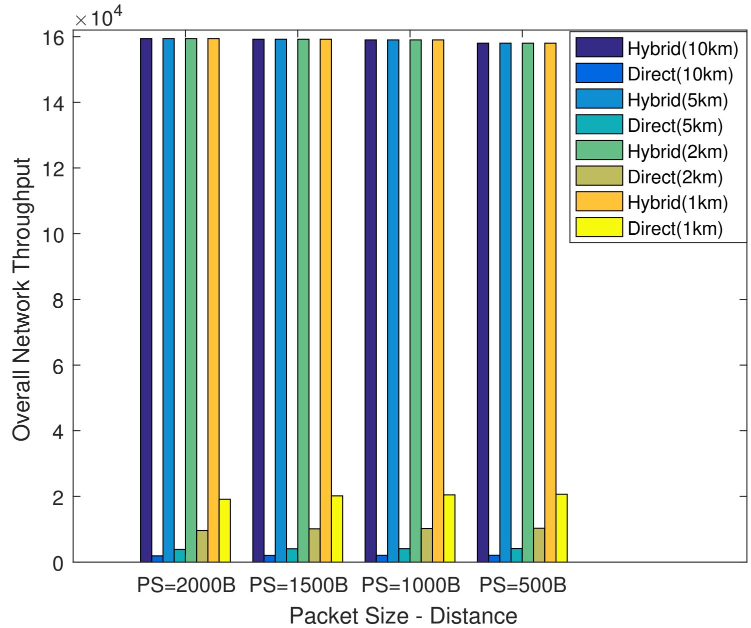


Figure 11: Throughput results of four AUVs

have a slightly lower data rate, as we assumed a constant rate-range product of 20 $kbps \times km$.

In the direct method, if applications start at the same time, we experience high collision rate. To deal with this issue, we use scheduling in the direct scheme where application start times have a lag to avoid collisions. As shown in Fig. 11, the aggregate throughput of the direct scheme is far less than that of the hybrid scheme. This is due to lower acoustic link rates in the direct scheme, which cause higher packet transmission delays. In the hybrid scheme, using the RTS/CTS mechanism for the RF links does not affect the network efficiency because of the higher data rates of the RF links.

This simulation highlights the difference between the hybrid and direct AUV-AUV communications in a network of four AUVs. As mentioned earlier, since the traffic load of RF links is far less than that of the acoustic links, the RTS/CTS mechanism is suitable for hybrid networks.

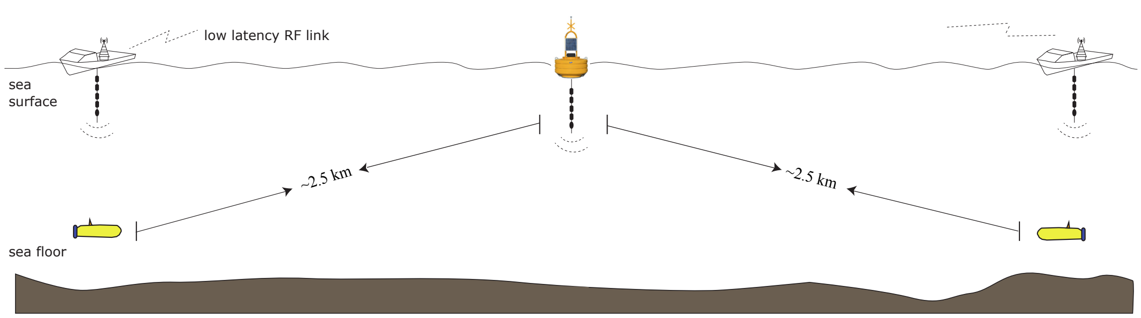
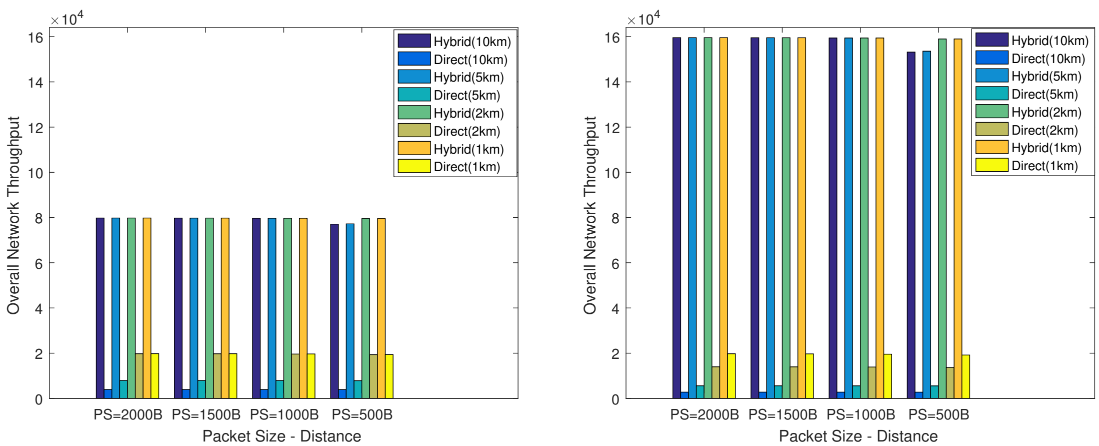


Figure 12: Infrastructure mode.

5.3 Third Scenario: Infrastructure-based networks

Underwater networks are often constructed with a centralized (infrastructure-based) structure, where all the nodes transmit their sensory information to a centralized entity, or an Access Point (AP). An AP will have another antenna to communicate with a sink node by using RF link. This scenario simulates either two or four AUVs communicating with one AP using the hybrid or the direct scheme. The AP is located equidistant from the AUVs. In the hybrid method, ASVs transfer the information collected from the AUVs to the AP using RF links. Fig. 12 illustrates two AUVs 5 km apart from each other. The AP is located half-way between the two AUVs at water surface and AUVs navigate at depth of 50m similar to previous scenarios.



(a) (b)

Figure 13: Aggregate throughput of variable packet sizes for (a) two and (b) four AUVs communicating with an AP equidistant from the AUVs.

The result of aggregate network throughput for two and four nodes are presented in Fig. 13. In the direct scheme, we use optimal packet scheduling (pipelining), where the AP is always receiving packets and an AUV transmits a packet with a lag. The lag is referred to as the packet transmission delay plus inter-frame space (IFS), which is 0.01 s in our simulations. For instance, if two AUVs are 2 km apart and the packet size is 2 kB, packet transmission delay (PTD) is 0.8 s. If the first AUV transmits at time $T = 0s$, the second AUV transmits at time $T = PTD + IFS = 0.81$ s, the third AUV at time $T = 2 * (PTD + IFS) = 0.162s$, and so on. The acoustic link data rate is also computed based on the same rate-range product as before, 20 $kbps \times km$. In case of two AUVs separated by 2 km, the acoustic link data rate is 20 kbps for the AUV-AP link.

In the hybrid scheme, higher throughputs are achieved for larger packet sizes owing to smaller amount of control packets (RTS/CTS). Advantages of the hybrid scheme are more remarkable with increase in the network size or AUV-AUV distance.

6 Conclusion

With wide range of underwater applications, underwater acoustic sensor networks (UASNs) have recently gained more attention. The low bandwidth and long propagation delay of acoustic networks call for efficient MAC protocols and new architectures. By using ASVs at the sea surface, we designed a functional architecture for autonomous underwater operations with swarming-based ASV navigation and hybrid RF-Acoustic communications as its constituents. The connected RF backbone is maintained by a swarm of ASVs for enhanced data rates and much reduced end-to-end latency for AUV-AUV communications. We evaluated, via ns-3 simulations, the performance of hybrid RF-acoustic communications in comparison to direct underwater AUV-AUV acoustic communications.

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