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Resilience against Shipping Noise and Interference of the AHOI Acoustic Underwater Modem

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***Abstract*—Underwater Wireless Sensor Networks (UWSNs) and micro Autonomous Underwater Vehicles (μAUVs) enable diverse underwater monitoring and service applications; e. g., observation of water quality or identification of pollution. Reliable underwater communication for data transmission between sensors, μAUVs and base stations is required. The smartPORT acoustic underwater modem AHOI is a small, low-power and low-cost modem, which was developed for these applications. This paper evaluates the modem's resilience against shipping noise and packet interference in UWSNs. At first, noise and interference sources are presented, followed by a short description of the modems's countermeasures. At last, simulated noise of ships and Autonomous Underwater Vehicles (AUVs) with different distances to the noise source were added to the communication signals and evaluated. And in addition, packet interference was simulated and evaluated in a real-world scenario.**

I. Introduction

Exploration and monitoring of underwater sceneries is drawing considerable attention [1]. Recent examples are UWSNs such as HydroNode [2], SUNRISE [3] or services for example Robotic Vessels as-a-Service (RoboVaaS) [4]. In all cases, reliable underwater communication is a major requirement. Due to the strong attenuation of the electro-magnetic wave in the water, most of the communication interfaces use an acoustic communication (e.g. [5], [6]). Many applications are located in ports and rivers and include several devices. Ships and AUVs produce acoustic noise, which could disturb the acoustic communication. In addition, in a network of acoustic modems packet collisions can occur when several modems transmit simultaneously.

In the following sections, we evaluate the AHOI modem's resilience against shipping noise and packet interference in a network. A preliminary study was presented in [7]. The resilience tests were used to simulate the modem behavior in DESERT [8], a simulator for underwater networks based on ns2. This paper extends the existing simulations with shorter distances to the noise sources (higher noise level at the receiver), an AUV noise simulation and additional interference combinations. Moreover, interference is tested in a real-world scenario. The interference evaluation is useful for prospective decision on a Medium Access Control (MAC) protocol.

II. AHOI - Acoustic Underwater Modem

The AHOI modem is a small, low-power and low-cost acoustic underwater modem (see Fig. 1 and [9], [10]), developed to be integrated into UWSNs or μAUVs (for example the HippoCampus [11]). The power consumption in idle and receive mode is around $300\,\mathrm{mW}$ and $2.1\,\mathrm{W}$ during data transmission with highest amplification. For acoustic signal reception and transmission, the AHOI modem uses an Aquarian Audio AS-1 hydrophone [12]. In case of the highest amplifier level, the transmission source level is between 150-160 $\mathrm{dB\,re\,\mu Pa^2\,@1\,m}$.

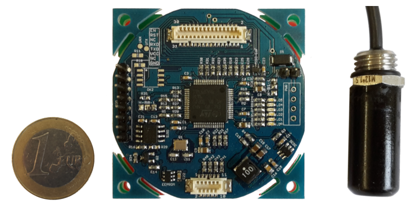


Fig. 1: AHOI acoustic underwater modem with hydrophone.

Signal processing is realized in software on the microcontroller, which allows a fast reconfiguration of frequency and coding setups. In the default setup, the modem uses an orthogonal Binary Frequency Shift Keying (BFSK) with $2.56\,\mathrm{ms}$ symbol duration and $781.25\,\mathrm{kHz}$ frequency spacing. Each symbol consists of four superimposed sinusoidal waveforms. To counter frequency cancellations caused by multipath propagation and to enhance the reliability against noise, each bit is repeated on three different carriers, and Frequency Hopping Spread Spectrum (FHSS) is applied to avoid inter-symbol interference. The modem has $25\,\mathrm{kHz}$ bandwidth around a center frequency of $62.5\,\mathrm{kHz}$. The default setup in combination with Hamming coding leads to a net data rate of $260\,\mathrm{bit/s}$ (up to $4.7\,\mathrm{kbit/s}$ are feasible with the current setup).

A. Receiver Design

Before the digitization of the received signal, the signal passes through an analog processing chain. At first, the signal is pre-amplified to have a higher signal level. Afterwards a highpass filter with cut-off frequency $f_c = 50\,\mathrm{kHz}$ reduces signal components with lower frequencies and a lowpass filter with cut-off frequency $f_c = 75\,\mathrm{kHz}$ reduces the higher parts. At last, the signal is amplified again. The amplification gain is controllable in the range from $60\,\mathrm{dB}$ to $96\,\mathrm{dB}$. Figure 2 shows the receiving characteristic for selected gain steps.

B. Hydrophone Characteristic

The AHOI modem uses a single transducer to receive and to transmit (see Sect. II). In Fig. 3 the Free-Field Voltage Sensitivity (FFVS) and Transmit Voltage Response (TVR) of the hydrophone are depicted. The FFVS in the range from

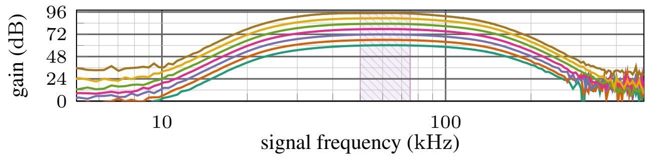
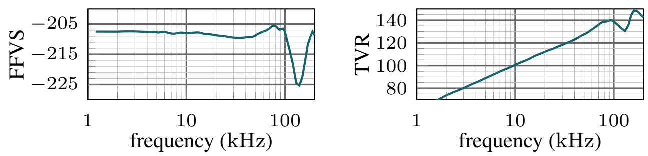


Fig. 2: Measured transfer function of the analog receiving signal chain of an AHOI modem in steps of $6\,\mathrm{dB}$.



(a) AS-1 as receiver (b) AS-1 as transmitter

Fig. 3: FFVS in $[\mathrm{dB\,re\,1V/\mu Pa}]$ and TVR in $[\mathrm{dB\,re\,1\mu Pa, 1V@1\,m}]$ of an Aquarian Audio AS-1 hydrophone [12].

$1\,\mathrm{kHz}$ to $100\,\mathrm{kHz}$ is almost linear ($\pm 2\,\mathrm{dB}$) and has a sensitivity of $-208\,\mathrm{dBV\,re\,1\mu Pa}$. Opposed to the FFVS, the TVR is highly frequency dependent. During a transmission, the modem compensates the frequency-dependent characteristic.

III. Fundamentals

This section presents the attenuation of acoustic signals in underwater scenarios and different ship and AUV noise profiles. Interference in underwater networks is discussed.

A. Acoustic Signal Attenuation

When the acoustic wave travels through the water, the signal is attenuated. The path loss depends on the frequency f and the distance d between sender and receiver. The attenuation is

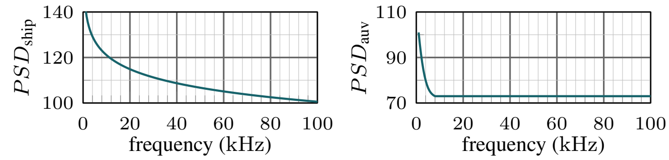
$$L(d, f) = L_{\text{spr}}(d) + L_{\text{abs}}(d, f) \quad (1)$$
$$= 20 \cdot n \cdot \log_{10}(d) + d \cdot \alpha(f)\ \mathrm{dB} \quad (2)$$

with spread loss L_{spr} and absorption loss L_{abs}. The path loss exponent n depends on the situation and environment. For a spherical spreading and a free-field assumption, the exponent is $n = 1$. In contrast to spread loss, absorption loss is frequency-dependent. The function $\alpha(f)$ models attenuation in relation to the frequency. Different models are discussed in [13], e.g. the Schulkin and Marsh formula. Assuming test conditions from Sect. V, typical absorption losses are less than $3\,\mathrm{dB/km}$ for frequencies up to $100\,\mathrm{kHz}$. Based on that, absorption loss is negligible in small communication distances compared to spread loss; e. g., $L_{\text{spr}}(100\,\mathrm{m}) = 40\,\mathrm{dB}$. Attenuation for short distances can be approximated with

$$L(d) = 20 \log_{10}(d)\,. \quad (3)$$

B. AUV and Shipping Noise

Ships and AUVs produce acoustic noise. The intensity and frequency depends, e. g., on speed and ship length. For acoustic noise modeling, the authors in [14] presented a detailed analysis of different noise sources, different ships and AUVs. In addition, an equation is derived to calculate noise Power Spectral Densities (PSDs). To evaluate the AHOI modem resilience against shipping noise, these noise PSDs are used. Two models are depicted in Fig. 4. At first a noise model for



(a) $180\,\mathrm{m}$ cargo ship, $15\,\mathrm{knots}$ (b) Bluefin Robotics AUV

Fig. 4: Noise PSD in $[\mathrm{dB\,re\,\mu Pa^2/Hz}]$ produced by a ship and an AUV. The PSDs are derived with the equations presented in [14].

a $180\,\mathrm{m}$ cargo ship, traveling with a velocity of $15\,\mathrm{knots}$, and the second one for an AUV from Bluefin Robotics [15]. In both cases, the acoustic noise emitted by ship and AUVs have highest PSDs below $10\,\mathrm{kHz}$.

C. Signal Interference

In UWSNs, multiple nodes transmit and receive data. The simplest way is to start a data transmission, when the data was recorded. This concept can lead to packet interference if several nodes need to use the transmission channel at the same time and packets overlap at the receiver. A more coordinated transmission medium access (Carrier Sense Multiple Access, CSMA), is to listen to the channel before the transmission. If the channel is unused, the sender starts the transmission. Opposed to the speed of light in a wireless over-water transmission (using electro-magnetic waves), the speed of sound in an underwater scenario is much lower. The speed of sound depends on temperature, salinity, depth and is approximately $1500\,\mathrm{m/s}$. For short distances, propagation delays are in the millisecond range; e. g., for $150\,\mathrm{m}$ a propagation time of $100\,\mathrm{ms}$ (in contrast to propagation times less than $1\,\mathrm{ns}$ for wireless over-water communication). Based on that, CSMA is difficult to apply compared to wireless over-water communication. Additionally, in a network with μAUVs, protocols with time synchronization and a fixed communication time slot for each node, e. g., Time Division Multiple Access (TDMA), are impractical due to the high variation of the propagation time (due to mobility). In sum, media access is a critical point in UWSN and there is a risk of packet interference. An extensive discussion on UWSN media access can be found in [1].

IV. Experimentation Setup

The resilience against shipping noise and packet interference was evaluated via simulation and a real-world scenario.

A. Simulation

A simulation was performed to assess the resilience against ship and AUV noise. The noise was generated offline and added to different recorded packets. A single AHOI modem was used to receive the signal, which was generated with an arbitrary signal generator (TiePie Handyscope HS5, $200\,\mathrm{kHz}$ sampling). The signal generator simulated the hydrophone voltage response (see FFVS in Sect. II-B) for different PSDs and the signal strength was calculated with Eq. (3). Figure 5 shows the PSDs of received packets at the receiver side (neglecting all propagation paths besides Line-of-Sight (LOS)) for distances to transmitter

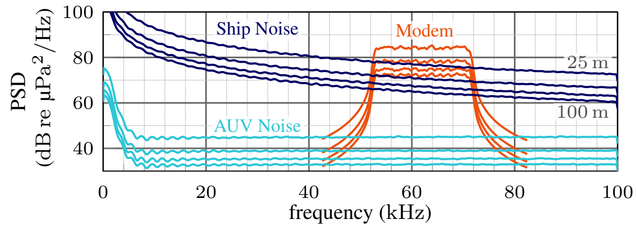


Fig. 5: PSDs of the simulated modem signals and additional shipping noise. The PSDs correspond to received signals (packets or noise) with $d_{\text{M}}, d_{\text{ship}}, d_{\text{AUV}} \in \{25\,\text{m}, 50\,\text{m}, 75\,\text{m}, 100\,\text{m}\}$ distance to the transmitter or noise source.

$d_{\text{M}} \in \{25\,\text{m}, 50\,\text{m}, 75\,\text{m}, 100\,\text{m}\}$ and distances to the noise source $d_{\text{ship}}, d_{\text{AUV}} \in \{25\,\text{m}, 50\,\text{m}, 75\,\text{m}, 100\,\text{m}\}$. During the simulations, different noise profiles were added to the packets. The noise profiles were generated in according to Sect. III-B and also shown in Fig. 5. For each combination of ship or AUV noise level and communication signal strength, 100 transmissions were simulated (with 32 B payload per packet).

In addition to ship and AUV noise, other underwater modems in a network could disturb the transmission (see Sect. III-C). To evaluate the effect of packet interference and the resulting Packet Reception Rate (PRR), the same simulation setup was used. Instead of additional simulated noise, a second recorded packet was added to the generator samples. All packets carried 32 B payload and had a signal duration of $T_{\text{pkt}} = 1.3\,\text{s}$, including the synchronization symbols. During the simulation two modems ($\mathcal{M}_1$ and $\mathcal{M}_2$) transmitted packets with different delays $\Delta t \in \{-1.25 \cdot T_{\text{pkt}}, -1 \cdot T_{\text{pkt}}, ..., 1.25 \cdot T_{\text{pkt}}\}$. The time Δt is the reception time difference between $\mathcal{M}_1$ and $\mathcal{M}_2$ at the receiver side w. r. t. the reception of the packet from $\mathcal{M}_1$. For example, $\Delta t < 0$ means the packet from $\mathcal{M}_2$ arrives before the packet sent by $\mathcal{M}_1$. $|\Delta t| > T_{\text{pkt}}$ is a reception without interference. The signal strengths of the received packets are similar to the noise test (see Fig. 5).

B. Real-World Evaluation

The real-world evaluation took place at the Port of Harburg, a small marina in Hamburg (see Fig. 6). It was a warm and windless day in June 2019 with 19.5 °C water temperature. In all cases, the hydrophones were placed 1.5 m under the water surface. During the evaluation three AHOI modems were used. The receiver was placed at a fixed position and two transmitters at the setups (1) $d_{\text{M1}} = 25\,\text{m}$, $d_{\text{M2}} = 25\,\text{m}$ (2) $d_{\text{M1}} = 25\,\text{m}$, $d_{\text{M2}} = 40\,\text{m}$. Each combination of setup and delay $\Delta t \in \{-1.5 \cdot T_{\text{pkt}}, -0.5 \cdot T_{\text{pkt}}, 0, 0.5 \cdot T_{\text{pkt}}, 1.5 \cdot T_{\text{pkt}}\}$, 100 packets with 32 B payload were transmitted. Due to serial connection and internal packet handling of the modems, the exact transmission time was not controllable (a few milliseconds difference). Both modems were connected to a laptop and we waited Δt between the transmission initialization and neglected the underwater propagation time. Compared to the packet overlap in the seconds range, these limitations are small (in the millisecond range). For $\Delta t = 0$ the transmission from $\mathcal{M}_1$ is initialized first.


Fig. 6: Test area of our real-world evaluation at a port in Hamburg.

V. Results

A. Simulation

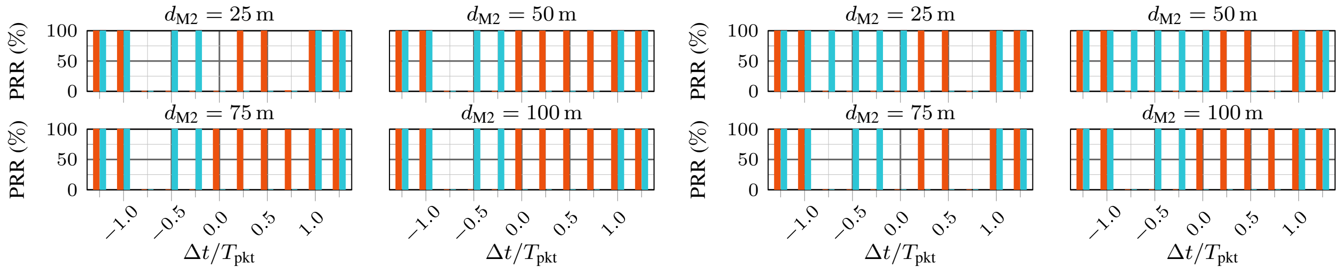
At first, the resilience against ship and AUV noise was evaluated. The ship noise affected packet reception in two cases and in the other cases all transmitted packets were received. The combination $d_{\text{ship}} = 25\,\text{m}$, $d_{\text{M}} = 75\,\text{m}$ resulted in 97 % and $d_{\text{ship}} = 25\,\text{m}$, $d_{\text{M}} = 100\,\text{m}$ in 26 % received packets. In both cases, the noise PSD is higher than the communication signal PSD. As a simplification during the simulations, the noise source was assumed as a point source and d_{ship} was smaller than the ship length (180 m). In general, the ship noise sources are distributed over the ship hull and the received signal level lower. The noise emitted by an AUV has a lower PSD. As expected, in all simulations with AUV noise profiles all packets were received. In sum, the modem is resilient against ship and AUV noise.

The second evaluation simulated packet interference between two modems and different communication distances. Due to space limitations, Fig. 7 depicts only the results for $d_{\text{M1}} \in \{25\,\text{m}, 75\,\text{m}\}$ in combination with $d_{\text{M2}} \in \{25\,\text{m}, 50\,\text{m}, 75\,\text{m}, 100\,\text{m}\}$. The results of the evaluation are: (1) Without interference ($|\Delta t| \geq T_{\text{pkt}}$) all packets from $\mathcal{M}_1$ and $\mathcal{M}_2$ were received. (2) The first packet (w. r. t. the arrival at the receiver) is received, also for the case that the second transmitter is nearer. (3) For the case $\Delta t = 0$ and $d_{\text{M1}} \neq d_{\text{M2}}$ the packet from transmitter with a shorter distance is received. (4) For $\Delta t = 0$ and $d_{\text{M1}} = d_{\text{M2}}$ the PRR goes to zero. An exception are the cases: (a) $\Delta t = -0.75 \cdot T_{\text{pkt}}$ and $d_{\text{M1}} \leq d_{\text{M2}}$ (b) $\Delta t = \ 0.75 \cdot T_{\text{pkt}}$ and $d_{\text{M1}} \geq d_{\text{M2}}$ The generated simulation signals in Fig. 8 gives an explanation for the exception. For the case $\Delta t = 0.75 \cdot T_{\text{pkt}}$ is a signal cancellation, which distorts the packet reception.

Based on the simulation, the modem is resilient against interference in the most cases. The resilience is independent of the packet overlap and dependents on frequency cancellations between the overlapping packets. Currently, other modulation schemes are under development to avoid cancellations [16].

B. Real-World Evaluation

Figure 9 depicts the results of the real-world evaluation. Opposed to the simulation, which simulates the LOS path only, a real-world scenario consists of multiple propagation paths and additional noise. Multipath propagation leads to symbol interference and lowers the PRR. The results of the evaluation are: (compared to the four points in Sect. V-A): (1) Without interference ($|\Delta t| \geq T_{\text{pkt}}$) the PRR was between $87 - 100\,\%$. (2) The first received packet wins with an average PRR of 68 % (in the case $\Delta t = 0$, $\mathcal{M}_1$ transmits



(a) Distance to $\mathcal{M}_1$: $d_{M1} = 25\,\mathrm{m}$ (b) Distance to $\mathcal{M}_1$: $d_{M1} = 75\,\mathrm{m}$

Fig. 7: Packet interference simulation between $\mathcal{M}_1$ and $\mathcal{M}_2$. The time Δt is the difference between the reception of the packet from $\mathcal{M}_1$ and $\mathcal{M}_2$ at the receiver side (w. r. t. the reception of the packet from $\mathcal{M}_1$). The received signal strength was calculated w. r. t. the transmission distances $d_{M1} \in \{25\,\mathrm{m}, 75\,\mathrm{m}\}$ and $d_{M2} \in \{25\,\mathrm{m}, 50\,\mathrm{m}, 75\,\mathrm{m}, 100\,\mathrm{m}\}$. Red bars show the PRRs from $\mathcal{M}_1$ and blue bars from $\mathcal{M}_2$.

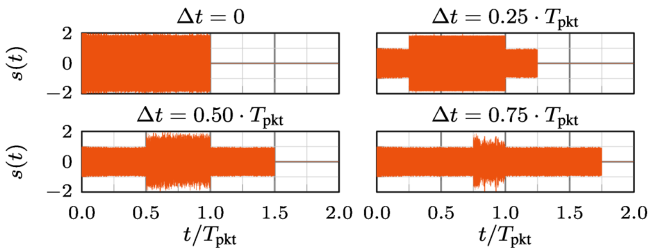


Fig. 8: Offline generated simulation signals $s(t)$ with packet interference. The amplitudes of both packages are normalized to 1.

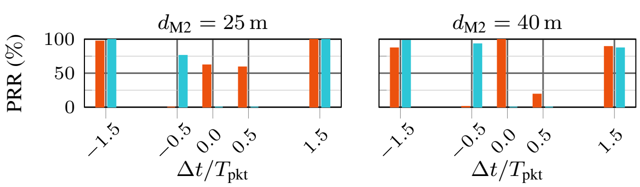


Fig. 9: Results of the packet interference real-world evaluation. Receiver and $\mathcal{M}_1$ were fixed with distance $d_{M1} = 25\,\mathrm{m}$. Red bars show the PRRs from $\mathcal{M}_1$ and blue bars from $\mathcal{M}_2$.

a few milliseconds before $\mathcal{M}_2$). The points (3) and (4) were not included in the evaluation. Similar to signal cancellation during the simulation, at $d_{M2} = 40\,\mathrm{m}$ and $\Delta t = 0.5 \cdot T_{\mathrm{pkt}}$ the PRR decreased to $19\,\%$. Also in a repetition of the experiment ($d_{M1} = 25\,\mathrm{m}$, $d_{M2} = 40\,\mathrm{m}$, $\Delta t = 0.5 \cdot T_{\mathrm{pkt}}$) the PRR reduced to $7\,\%$. In both cases, $99\,\%$ and $86\,\%$ of the packet headers were received. This leads to the assumption, that the second packet cancels the signals from the first during the payload reception.

In sum, the real-world evaluation supports the general finding from the simulation with the LOS signal. Due to multipath propagation and addition noise, the PRR decreased in the case of packet interference.

VI. Conclusion

We showed with a simulation that the modem is resilient against ship and AUV noise. In addition, we analyzed packet interference with simulations and a real-world tests. In many cases, the modem is resilient against packet interference. Based on our findings, it will be possible to choose a MAC protocol for UWSNs or swarms of μAUVs equipped with our AHOI modem.

Acknowledgment

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References

[1] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater Sensor Networks: Applications, Advances, and Challenges," *Philosophical Transactions of the Royal Society–A*, vol. 370, no. 1958, 2012.

[2] D. Pinto, S. S. Viana, J. A. M. Nacif, L. F. M. Vieira, M. A. M. Vieira, A. B. Vieira, and A. O. Fernandes, "HydroNode: A Low Cost, Energy Efficient, Multi Purpose Node for Underwater Sensor Networks," in *37th IEEE Conf. on Local Computer Networks*, Clearwater, FL, USA, 2012.

[3] "SUNRISE FP7 research project," http://fp7-sunrise.eu, ac.: 2019/06/03.

[4] A. Signori, F. Steinmetz, F. Campagnaro, D. Zordan, M. Zorzi, and C. Renner, "Poster: Underwater Communications for the Robotic Vessels as-a-Servic Project," in *13th ACM Int. Conf. on Underwater Networks & Systems (WUWNet)*, Shenzhen, China, 2018.

[5] E. Gallimore, J. Partan, I. Vaughn, S. Singh, J. Shusta, and L. Freitag, "The WHOI Micromodem-2: A Scalable System for Acoustic Communcations and Networking," in *MTS/IEEE Oceans Conf. & Expo. (OCEANS)*, 2010.

[6] Evologics GmbH, "Underwater Acoustic Modems," http://www.evologics.de/en/products/acoustics/, ac.: 2019/06/03.

[7] F. Campagnaro, F. Steinmetz, A. Signori, D. Zordan, C. Renner, and M. Zorzi, "Data Collection in Shallow Fresh Water Scenarios with low-cost Underwater Acoutic Modems," in *5th Int. Conf. & Exhibition on Underwater Acoustics (UACE)*, Crete, Greece, 2019.

[8] F. Campagnaro, R. Francescon, F. Guerra, F. Favaro, P. Casari, R. Diamant, and M. Zorzi, "The DESERT underwater framework v2: Improved capabilities and extension tools," in *3th IEEE Underwater Communications & Networking Conf. (UComms)*, Lerici, Italy, 2016.

[9] C. Renner and A. J. Golkowski, "Acoustic Modem for Micro AUVs: Design and Practical Evaluation," in *11th ACM Int. Conf. on Underwater Networks & Systems (WUWNet)*, Shanghai, China, 2016.

[10] J. Heitmann, L. Bublitz, T. Kortbrae, and C. Renner, "Evolution of an Acoustic Modem for Micro AUVs," in *16th GI/ITG KuVS Fachgespräch "Sensornetze" (FGSN)*, Hamburg, Germany, 2017.

[11] A. Hackbarth, E. Kreuzer, and E. Solowjow, "HippoCampus: A Micro Underwater Vehicle for Swarm Applications," in *IEEE Int. Conf. on Intelligent Robots & Systems (IROS)*, Hamburg, Germany, 2015.

[12] Aquarian Audio & Scientific, "AS-1 Hydrophone," http://www.aquarianaudio.com/as-1-hydrophone.html, ac.:2019/05/27.

[13] R. J. Urick, *Principles of Underwater Sound 3rd Ed.* Peninsula, 1996.

[14] E. Coccolo, F. Campagnaro, A. Signori, F. Favaro, and M. Zorzi, "Implementation of AUV and Ship Noise for Link Quality Evaluation in the DESERT Underwater Framework," in *13th ACM Int. Conf. on Underwater Networks & Systems (WUWNet)*, Shenzhen, China, 2018.

[15] General Dynamics, "Bluefin SandShark UUV," https://gdmissionsystems.com/products/underwater-vehicles/bluefin-sandshark-autonomous-underwater-vehicle, ac.: 2019/05/27.

[16] F. Steinmetz, J. Heitmann, and C. Renner, "A Practical Guide to Chirp Spread Spectrum for Acoustic Underwater Communication in Shallow Waters," in *13th ACM Int. Conf. on Underwater Networks & Systems (WUWNet)*, Shenzhen, China, 2018.