PERFORMANCE ASSESSMENT OF UNDERWATER ACOUSTIC MODEMS OPERATING SIMULTANEOUSLY AT DIFFERENT FREQUENCIES IN THE PRESENCE OF BACKGROUND IMPULSIVE NOISE EMITTED BY A SPARKER

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Abstract: *Paper describes work done in the scope of the WiMUST (Widely scalable Mobile Underwater Sonar Technology) project towards the development of a combined positioning and data communication system for a group of AUVs towing streamers together and a companion support vessel carrying an acoustic sparker, with a view to geotechnical surveying applications. In particular, the paper summarizes modelling and experimental results of short range acoustic communications (under 1000 m) using simultaneously a middle frequency modem (18-34 kHz) for the delivery of payload data from the AUVs to the surface vessel and a high frequency modem (42-65 kHz) for the exchange of service and positioning data among the AUVs undergoing formation control. The particular characteristics of these tests consisted in the presence of strong background impulsive noise generated by means of a powerful sparker, typically used for seismic surveys. During experimental tests, each of the two selected modems types (S2CR18/34 and S2CR42/65) showed similar performance when operating either separately or simultaneously with the other and in presence of the impulsive noise.*

Keywords: *underwater acoustic communication, underwater positioning, AUV*

1. INTRODUCTION

According to WiMUST [[1]] system specifications there are the three major data sets needed to be communicated via hydro-acoustic channel: 1) fragments of seismic data, 2) AUV navigation, guidance and control data, 3) service data (e.g. synchronisation date) for distribution among vehicles.

Fragments of seismic data must be transmitted in real time from each AUV to the vessel (to the terminal). These fragments serve for in-situ quality estimation of collected seismic data sets. AUV navigation, guidance and control data must be communicated to all the vehicles in real time for adaptation of the vehicles' formation (during seismic shooting) to meet survey coverage requirements. Service data communicated among AUVs must be distributed in real time and e.g. serve for synchronization, starting/finishing changing the mission set up during operation of AUVs underwater.

The underwater communication architecture implies the possibility to scale the approach toward a large number of vehicles. Therefore, communication of the positioning information from the terminal (or from any reference device containing global or local coordinates) must occur in the course of parallel unidirectional data delivery (otherwise any bidirectional data exchange will lead to large time gaps between successive position estimations of every AUV). Time synchronisation of the AUVs must be provided due to synchronisation algorithms based on parallel unidirectional delivery of synchronisation data from a reference clock distributing global or local time among AUVs through hydro-acoustic channel (as a back-up solution instead of atomic clock based AUVs synchronisation). Seismic data transfer from each AUV to the terminal must happen so fast that the operator on the vessel (at the terminal) would have data updates each 30-60 seconds from all the AUVs for supervising the process of seismic data collection. Since seismic data are relatively large data sequences (at least 10 kbit each), this problem has to be solved by means of hydro-acoustic modems providing relatively high data rates.

Provision of a communication link simultaneously to all three major data sets implies intensive exploitation of the hydro-acoustic medium. The data sets were sorted out in two groups: 1) not requiring high bitrate and 2) requiring high bitrate. Correspondingly two hydro-acoustic modems operating in different frequency bands were selected for simultaneous communication of different data sets. An application of two hydro-acoustic modems simultaneously represents a non-trivial task (already because of a narrow frequency bands available in hydro-acoustic communications). But, since geo-acoustic survey supposes permanent emission of strong (exciding 200 dB re 1 uPa) and wideband sparker pulses (less than 250 ms) into hydro-acoustic environment, underwater communication in WiMUST represents even more challenging task.

Next subsections contain experimental material 1) evaluating compatibility of different modems operating simultaneously in different frequency bands, and 2) evaluating compatibility of the hydro-acoustic communication with the sparker background activity (strong impulsive noise).

2. EXPERIMENTS ON COMPATIBILITY OF ACOUSTIC MODEMS OPERATING IN NEIGHBOURING FREQUENCY RANGES

Conditions. Two middle frequency (MF) modems operating in frequency band 18-34 kHz and two modems with higher operation frequencies (HF), 42-65 kHz, were used in experiments. Both modems are built upon S2C Technology [[2]] and manufactured by Evologics GmbH.

MF modems S2C18/34 contained an acoustic transducer with a smooth transmitting voltage response between 18 and 34 kHz, varying by up to 6 dB at the frequency band edges. The transducer had a weak resonance at 26 kHz. Its directivity pattern was omnidirectional in horizontal plane and had a weakly expressed directivity in vertical plane (an opening angle of about 120 degrees). During experiments, acoustic signals were transmitted at 178 dB re 1 uPa/m.

HF modem S2C42/65 contained an acoustic transducer with a smooth transmitting voltage response in the operation frequency range between 42 and 65 kHz, varying by up to 6 dB at band edges. The transducer had a weak resonance at 54 kHz. Its directivity pattern was conical with an opening angle of about 90 degrees (by -6 dB), However, in beyond this cone (up to ±90 degrees) the transmitting phase response was almost linear over entire frequency band, and the transmission voltage response was slowly weakening: e.g. at angles ±90 degrees from the acoustic axis of the transducer, the source level was about -13..-14 dB in relation to nominal one (at its acoustic axis). This circumstance allowed to involve this modem into tasks (yet in smaller operation ranges) requiring a hemispherical beam pattern. During the experiments, acoustic signals were transmitted at the source level 176 dB re 1 uPa/m.

Each pair of the modems transmitted seismic data as so called Burst Data (Burst Data – a DMAC protocol's special message type [[3]]) exploiting ARQ protocol for retransmission of damaged data packets (acknowledged as NACK). In this mode data were transmitted as a train of packets (user specified parameter, set up in this test to 10 packets per burst). Each packet contained synchronisation pulses and a header. Each burst contained a short service packet in the end of the packets train.

The modems were deployed at the same depth (1 m) from a jetty in Werbellinsee (water depth under the jetty was about 5 m). The modems were arranged in a line: HF modems in a distance of 25 m from each other, and MF modems 1 m behind HF modems, i.e. in a distance of 27 m from each other. The arrangement of the modems is shown in Fig. 1.

MF <--1m--> **HF** <-----------25m----------> **HF** <--1m--> **MF**

Fig. 1. Arrangement of the modems in compatibility experiments

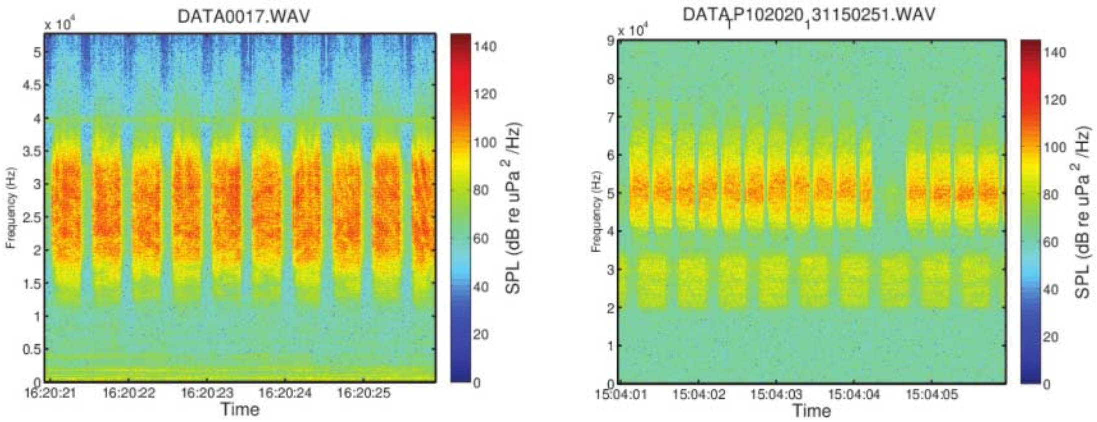
The weather was windy: the wind reached 21 km/h (about 4 Bft), wave height about 0.4 m. Due to "rough sea" conditions (wave height was comparable to the modem depth), signal propagation conditions varied. However, averaging over time the results of different modem pairs were valid for comparison. The whole set of experiments was conducted over 2.5 hours.

Each pair of the modems was used both for data transmission and data reception. Transmission by one modem pair was executed simultaneously with the other modem pair.

In one scenario, one modem of each pair acted as source, another as recipient. The source always sent a file of the size 10 kbytes, and the recipient sent service data with acknowledgements back to the source. Data transmission was executed cyclically during 30 minutes. In this scenario, data packets in each frequency band (belonging to different modem pairs) were delivered to their corresponding recipients asynchronously/simultaneously, thus imitating real conditions of data delivery (positioning, synchronisation, seismic data) during future WiMUST missions.

In second scenario, the conditions were even more complicated. Both sides of each modem pair acted as data sources asynchronously transmitting into hydro-acoustic medium data streams each 10 kBytes in size (so performing full-duplex with time separation, executed automatically by the modems providing transparent full-duplex mode to their host computers). The other side of each modem pair inserted among their own payload transmissions also service packets containing acknowledgements to the opposite side. In this scenario, the occupation of the acoustic medium was notably larger providing an opportunity to carry out the compatibility tests in most complicated conditions.

Results. Following figures (Fig. 2a,b) illustrate spectrograms of two modems acoustic activity, particularly a spectrogram for the MF modem (Fig. 2a), and a spectrogram for two modems, MF and HF, operating simultaneously (Fig. 2b). The measurements were done by means of the hydrophone type TS-1. Spectrogram in Fig. 2a represents an FFT analysis of 5s section of signal recorded during MF communication (snapshot length of 0.02 s Hanning window 50 % overlap and a factor 2 zero padding). Spectrogram in Fig. 2b shows an example of FFT analysis of 5s recording during simultaneous MF and HF communication (snapshot length of 0.02 s Hanning window 50 % overlap and a factor 2 zero padding).

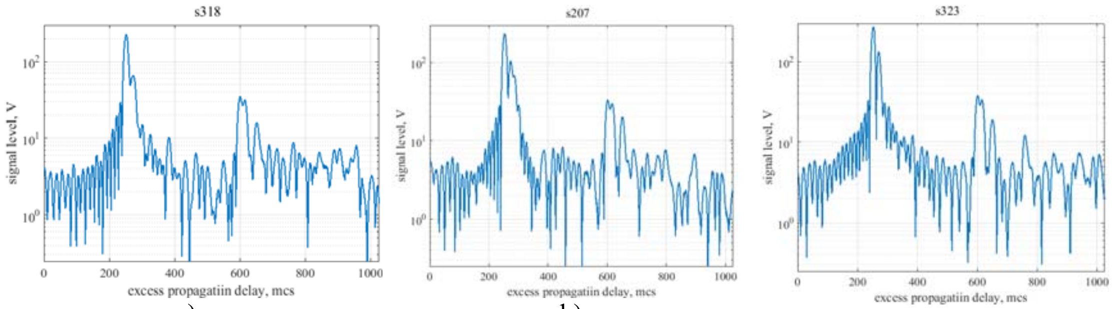


a) b)

Fig. 2. Spectrograms of the modems acoustic activity: a) modem S2CR18/34 only, b) two modems, S2CR18/34 and S2CR42/65, operating simultaneously

As follows from Fig. 2 the out-of-band energy of both modems is rather minor. For instance, measuring the power spectral density at 5 kHz beyond left and right edges of the nominal frequency band, the power spectral density falls down to more than 40 dB. Fig. 2b illustrates the separation of frequency bands occupied by the modems operating simultaneously. The difference between the central frequencies of these modems is 16.5 kHz, the mutual (inter-channel) interference of these modems at their central frequencies remained under –20 dB.

One of the most important characteristics of the underwater acoustic channel – intensity of multipaths *vs* excess propagation delay, registered during compatibility tests at Werbellinsee, is given in Fig. 3. As follows, the channel was characterised with two groups of multipath arrivals. The first one consisted of a dominating arrival and a delayed one (delay about 45 us). The second one consisted of three arrivals delayed (in relation to the dominating one) on 340 us, 385 us, and 420 us, correspondingly. The presence of the dominating arrival related this channel to the Racian ones. However, the presence of numerous multipath arrivals causes a relatively large complexity of the channel for high data rate communications (typical for underwater communication in shallow water channels).

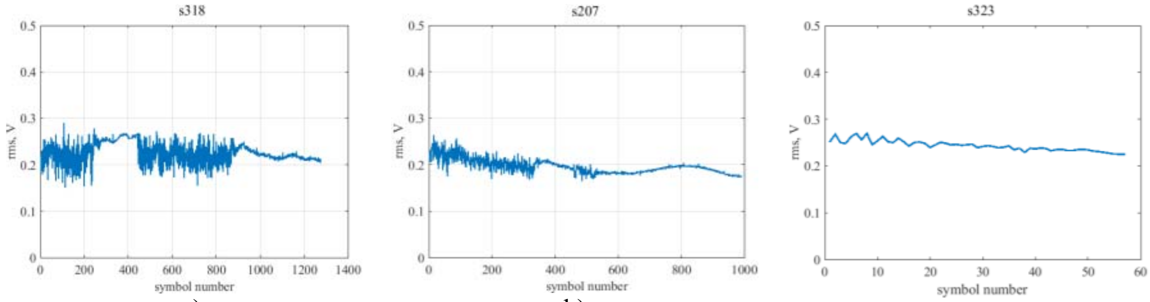


a) b) c)

Fig. 3. Intensity of multipaths vs excess propagation delay, registered during modems compatibility tests at Werbellinsee

Comparison of the communication performance of the HF modems (S2CR42/65) with and without simultaneous operation of the MF modems (S2CR18/34) in these conditions of underwater acoustic channel is given below.

In general, nominal bitrate of the HF modem without simultaneous operation of the MF modem mostly remained in the range 16-25 kbps. The effective bitrate (on the user interface) stayed between 4.2 and 8.1 kbps. However, data rates reduced after the MF modems started to operate in parallel. The effect of the operating MF modem onto the HF modems is presented in Fig. 4a,b,c. The sections of rms-curve, which contain well noticeable fluctuations, correspond to time intervals, in which signals from HF and MF modems interfered.



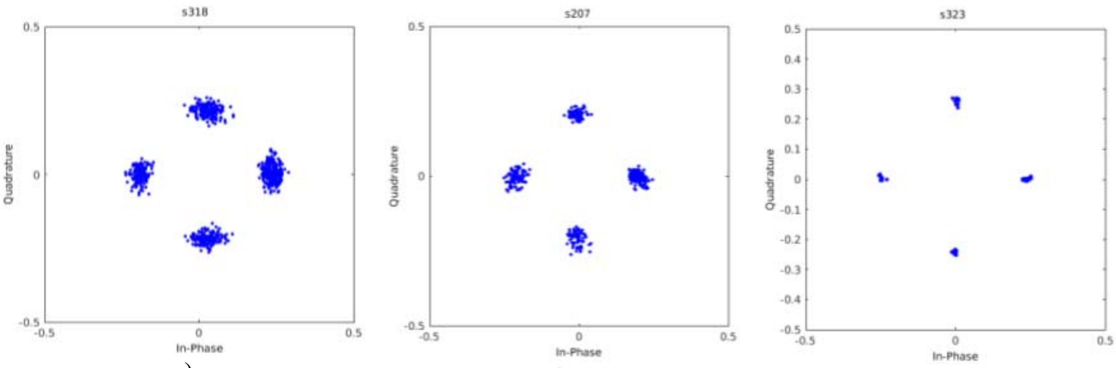
a) b) c)

Fig. 4. RMS of data symbols received by HF modem during parallel operation of the MF modem

The effect of simultaneous activity of the MF modem onto HF modem S2CR42/65 depends on the data rate (and, correspondingly, on the length of each data symbol, or on the amount of energy that each data symbol contains). This is illustrated in Fig. 4a,b,c.

In Fig. 4a the bitrate of the HF modem is 11904 bps, in Fig. 4b – 9259 bps, in Fig. 4c – 976 bps. The fluctuation of the RMS curve becomes less with decrease of the data rate, and correspondingly with increase of the energy contained in each data symbol (increase of data symbol energy).

Fig. 5 contains representation of phase spread of data symbols received by HF modem during parallel operation of the MF modem. In Fig. 5a – phase spread corresponds to data rate 11904 bps (corresponding RMS is in Fig. 4a), in Fig. 5b – to data rate 9256 bps (corresponding RMS is in Fig. 4b), in Fig. 5c – to the data rate 976 bps (corresponding RMS is in Fig. 4c). As follows from the comparison of Fig. 5a,b,c symbol estimations (phase and amplitude) were spread larger for high data rates. At the smallest data rate, 976 bps, the influence of the MF modem operating in parallel is nearly negligible. The standard deviation of phase measurements in Fig. 5s is only 1.06°. In Fig. 5s is higher and equal to 3.30°, in Fig. 5a is 5.42°.



a) b) c)

Fig. 5. Estimations of data symbols (phase and amplitude) received by HF modem during parallel operation of MF modem

When comparing results in tests, carried out with parallel operation of the MF modem, the achievable *nominal* data rates were approximately 1.8 times smaller (8-14 kbps) than in case of individual (no parallel) operation of the modems. *Effective* data rates (registered on the user interface) ranged typical between 2.3 and 5.2 kbps. This test validated the intention to achieve the payload data delivery time of about 3 s per single packet transmission (seismic data) with roughly 2 transmission cycles per minute, i.e. delivery of all seismic payload data from all ten AUVs of the demonstrator system can be completed less than in 30 s.

The performance of MF modem operating simultaneously with the HF modem was estimated in terms of the probability to deliver data packets (Instant Messages) from the first attempt. Almost in all conditions the success rate (in reception of instant messages) by the MF modem was between 90 and 100%. Only in one case the success rate dropped down to 70%. This happened in conditions when the MF modem was transmitting with the lowest source level, but the HF modem was transmitting with much larger source level, +12 dB.

3. PERFORMANCE ANALYSIS OF ACOUSTIC MODEMS DURING SPARKER EMISSIONS

Since geo-acoistic surveys foresee emission of strong broadband pulses during the mission, acoustic one of important steps during the project development was investigation of an influence of the sparker activity (impulsive noise) onto performance of acoustic modems.

The investigation has been carried out in close cooperation between Evologics and Geomarine. The acoustic activity of a sparker has been not only simulated, but also produced using industrial hardware manufactured by Geomarine.

A series of compatibility tests has been performed in a laboratory pool and Werbellinsee lake in Evologics premises.

The sparker equipment consisted of a sparker emitter, generator of sparker pulses with up to 2 kW and power source (Fig. 6a). For technical support at the Lake, e.g. deployment of the equipment in Werbellinsee, one of Evologics' boat has been used. The sparker emitter (Fig. 6b) was placed in a close vicinity to the modems (around 1 m). During acoustic communication between the modems, the sparker generated strong acoustic pulses, between 500 and 2000 W, with different emission periods, from 0.25 s to 1 s. The frequency range occupied with the sparker pulses was between 0.5 and 5 kHz.

a) b)

Fig. 6. Sparker equipment used in compatibility tests: a) power line from generator of sparker pulses and power source, b) sparker emitter

The sequence of sparker pulses, emitted with the period 1 s, is presented in Fig. 7. The record was made by means of calibration hydrophone Reson TC-4014 with voltage preamplifier VP1000. (Other records below have been done by means of this hydrophone, too.) The hydrophone was placed 1 m away from each transmitting modem (inside of its beam diagram, on its acoustic axis), and about 2 m away from the sparker.

The frequency spectrum of sparker pulses, recorded with no background activity of the acoustic modems, is presented in Fig. 8.

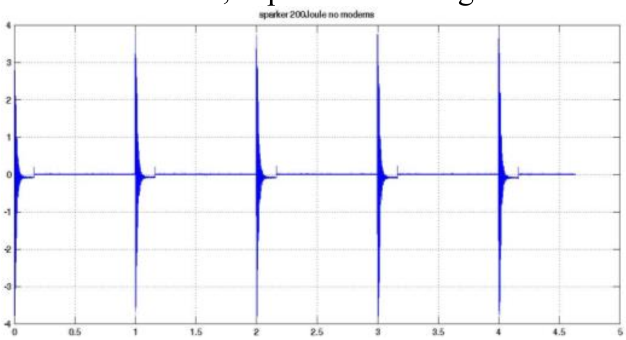


Fig. 7. Sequence of sparker pulses, no modem activity (time domain)

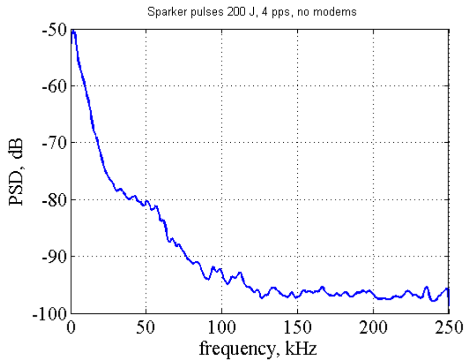


Fig. 8. Spectrum of sparker pulses, no modem activity

A sequence of MF modem signals, transmitted with no background activity of the sparker, is presented in Fig. 9. A sequence of MF modem signals, transmitted in parallel with background activity of the sparker (two pulses per second), is presented in Fig. 10.

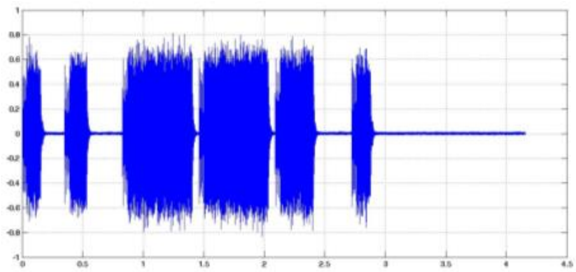


Fig. 9. MF modem signals (18-34 kHz), no sparker activity

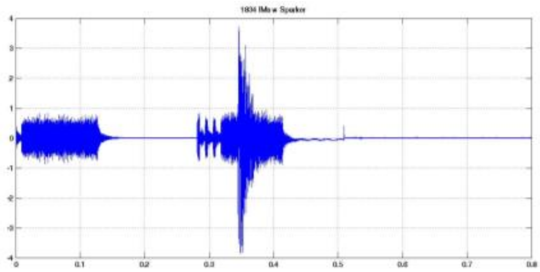


Fig. 10. MF modem signal (18-34 kHz), overlap with sparker pulse

As one can see in Fig. 10 the amplitude of the sparker pulses is significantly larger than the amplitude of the modem signal, what was necessary for imitating practically interesting acoustic conditions for the WiMUST system. Spectrum analysis of an overlap of the MF modem signals and the sparker pulses is shown in Fig. 11. As follows from the figure, the mutual influence of the modem activity and the sparker activity is rather moderate. An amount of sparker pulses energy penetrating into the frequency range of the MF modem is about 21-22 dB less than energies of the MF modem signals themselves. Also, an amount of modem signal energy penetrating into the frequency range of the sparker frequencies is 40-50 dB less than energies of the sparker pulses.

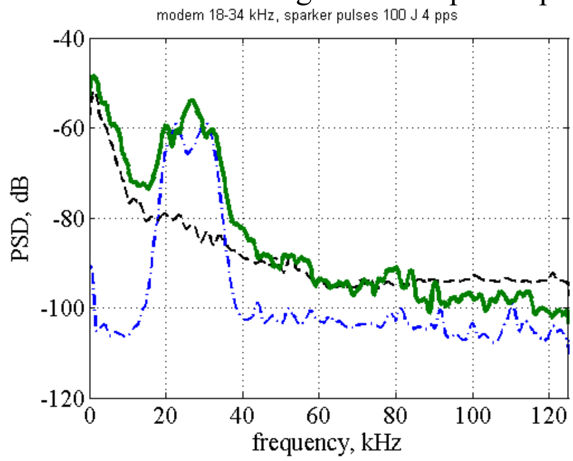


Fig. 11. Spectrum analysis of the MF modem signals (18-34 kHz) transmitted in time of the sparker activity (4 pulses per second): black line – sparker pulses spectrum, blue line – modem signals spectrum, green line – spectrum of a mixture of modem signals and sparker pulses

Regarding HF modem a spectrum analysis of its signals received in parallel of the sparker pulses (4 emissions per second) has shown even better relation: power spectral density of the modem signals was higher than power spectral density of the sparker pulses (in the modem's frequency range). Particularly, an amount of sparker pulses energy penetrating into frequency range of the HF modem was at least 25 dB less than energies of the HF modem signals themselves (and so the influence of the sparker activity to the HF modem performance was also less than to the MF modem).

The scope of the most important results, which were obtained during simultaneous testing of the modem performances S2CR18/34 and HF modems (pairwise) with a background activity of the sparker, is listed below:

- nominal bitrate of the MF modem S2CR18/34 was usually in the range 3.10-3.85 kbps. The effective bitrate (on the user interface) stayed between 1060 and 1180 bps;
- nominal bitrate of the HF modem S2CR42/65 stayed in the range between 12.1-22 kbps. The effective bitrate was between 3.6 and 6.2 kbps.

Comparison of the performances of MF and HF modems with and without background activity of the sparker demonstrated moderate decrease of the bitrate due to the disturbing acoustic pulses of the sparker. Data rate decrease was estimated as less than 20%.

4. CONCLUSIONS

The series of laboratory and at sea tests demonstrated a selection of hydro-acoustic modems capable for simultaneous operation: first one for the task of underwater acoustic positioning, and a second one for the task of payload data exchange with the surface vessel. The tests validated also the concept of simultaneous operation of two different acoustic modems during activity (in close vicinity) of a sparker at the surface emitting strong and broadband electric and acoustic pulses. No significant electromagnetic interference was observed on the electronics of the acoustic modems; and only a moderate decrease of the communication performance due to the disturbing acoustic pulses of the sparker was detected (the data rate decrease was less than 20%).

Demonstrated estimations of the effective bitrate (i.e. the bitrate at the user interface) for payload data delivery are approximately 3.5-5 kbit/s. This bitrate meets the specification requirements for development of the WiMUST project being enough for transmission of one seismic data block (1.25 kbyte) within a time of about 3 s. With this effective bitrate the expected time for data transmission from all the WiMUST vehicles (up to 10 AUVs) is less than 30 s – acceptable according to WiMUST system requirements.

The performance of MF modem operating simultaneously with the HF modem was estimated in terms of the probability to deliver data packets (Instant Messages) from the first attempt. Almost in all conditions the success rate (in reception of instant messages) by the MF modem was between 90 and 100%. Only in one case the success rate dropped down to 70%. This happened in conditions when the MF modem was transmitting with the lowest source level, but the HF modem was transmitting with much larger source level, +12 dB. This result motivates in future steps a development of a measure allowing to optimize in the AUV formation the source levels of different (simultaneously operating) modems so that the their signals (being received on the side of data recipient) would have comparable energies, and thus the reception success rate of data both by MF and HF modem would be good balanced.

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