CONSIDERATIONS OF ADAPTIVE DIGITAL COMMUNICATIONS IN UNDERWATER ACOUSTIC CHANNEL

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Down-link communication (DLC) and air transportable communication (ATAC) buoys as well as autonomous underwater vehicles (AUV) use acoustic links for gathering oceanographic data from underwater monitoring systems. The underwater channel propagation conditions are diverse in nature and require a special adaptive approach to the communication system design. The article presents a methodology for the communication systems design, combining modern radio standards experience, and hardware equipment to design and test the adaptive underwater data transmission systems. The testbed experiments should be preceded by the test being carried out under laboratory conditions using the underwater channel impulse responses collected at numerous measurement sessions in different reservoirs.

INTRODUCTION

A DLC buoy, dropped from aircraft or ships, conducts underwater acoustic research. It communicates with an underwater monitoring system by an acoustic link. An ATAC buoy is commendable from the aircraft and provides up-link communication using radio or cable interface, and down-link data transmission with the use of underwater acoustic communications (UAC). AUVs also use an acoustic link to communicate with the ship or other base station on the water surface. As the range of the AUV's deployable science instruments increase and their operating costs decrease, AUVs are likely to become increasingly used for sea exploration, oceanographic research and underwater installations monitoring. Other area of acoustic link applications are the military purposes of AUVs.

The DLCs and the ATACs, as well as the AUVs can work in different environment conditions, thus there is a diversity of underwater acoustic channels between the transmitter and receiver of the communication system. The UAC channel can be vertical or horizontal, shallow or deep water, surface interaction or not, short or long range, low or high frequency.

Depending on the channel geometry, there is a problem of reflection and refraction, which leads to the time dispersion of the transmitted signal. The Doppler effect, related to the movement of the AUV, results in a time-domain scaling of naturally broadband communication signal. Moreover, the UAC channel transmission properties are strongly conditioned by the specificity of its geographic location, which can change in time. The variability of transmission properties is diverse in nature. Depending on the phenomena under consideration, we have to deal with a scale of several months (seasons), several days and hours (tides, time of day), minutes (internal waves), a few seconds (surface waves) and the order of milliseconds (reflections, scattering).

Depending on the communications system scenario, there are different requirements for speed and reliability of transmission in the acoustic link. It may be slow but reliable transmission of the AUV's control signals, faster and still reliable measurement data transmission from an underwater monitoring system or as fast as possible video transmission from underwater cameras. Thus, there is no typical UAC problem. The physical layer of the data transmission should be as flexible as possible.

The unexpected successes of formerly unreliable radio communications, limited to government services, and nowadays common and universal, is a challenge and inspiration for the designers and users of underwater communications. Modern radio communication standards are based on adaptive modulation and coding technique (AMC). The UAC channels show some resemblance to radio channels, accumulating, however, most of the adverse properties. The conception of adaptive underwater communication should extend the flexibility of solutions used in modern radio standards.

The design methodology of adaptive acoustic links working in any propagation conditions should take advantage of the experience of modern radio standards. The research in radio communications is mostly based on simulations using established propagation models. The adaptive UAC testbed experiments should be preceded by a test carried out under laboratory conditions using the underwater channel impulse responses collected at numerous measurement sessions in different reservoirs.

1. CONCEPTION - LINK ADAPTATION

The UAC system should be reconfigurable according to the the sonobuoy's or AUV's working scenario and the communication channel instantaneous propagation conditions. Thus, there is a need to develop and implement data transmission algorithms matching the UAC system physical layer parameters to dynamically varying channel conditions, in order to ensure the expected performance in any geographical conditions, in both the deep ocean channel and tough shallow inland water channels.

To achieve this goal, it is necessary to determine how to measure the transmission conditions of the channel. Next, the reconfigurable parameters of the communication protocol physical layer should be chosen. It is also necessary to determine which of these parameters should be set up for the duration of the task, and which should be matched every time the propagation conditions change significantly.

In wireless communications, the physical layer of the transmission protocol is matched to the radio link propagation conditions. The procedure is known as link adaptation (LA). Adaptive communication system improve the rate of transmission, and bit error rates, by exploiting the channel state information (CSI) that is present at the transmitter. An adaptive system uses both the long-term knowledge about the channel statistical characteristics (statistical CSI), and measured instantaneous system performance (instantaneous CSI).

The statistical CSI includes the type of fading distribution and the average channel gain. The fading distribution determines the mathematical model of the channel, and thus the channel conditions parameterization method. Wireless channels are described as a stochastic process with the Rayleigh distribution. Under this assumption the channel is fully characterized by the second-order statistics. Moreover, time-varying multipath propagation channels are assumed to be wide sense stationary (WSS) with uncorrelated scattering (US). The WSSUS assumption allows for simultaneous modeling of time dispersion leading to the frequency selectivity of the channel, and time variability resulting in frequency dispersion. The transmission parameters, such as the time-delay spread, Doppler spread, coherence time and coherence bandwidth can be defined based on the transmission characteristics. They determine the choice of physical layer parameters that minimizes the risk of time and frequency fading in the transmitted signal and thus allows the best possible protection against interference in difficult channels [1].

As in the case of radio channels, the UAC channel can also be described as a stochastic process with a Rayleigh distribution. Moreover, in some cases the WSSUS assumption can be used [2]. In the case of non-WSSUS channels, the regions of local coherence and stationarity in time and frequency domains, where the WSSUS assumption is satisfied, are searched for. As a result, the parametric description is being extended onto a broader class of communication channels.

The instantaneous CSI describes current channel conditions. It gives an opportunity to adapt the transmitted signal to the channel instantaneous propagation conditions and thereby optimize the received signal to achieve lower bit error rates. In a wireless system the instantaneous CSI is represented by the channel quality indicator (CQI). Typically, a high value CQI is indicative of a channel with high quality and vice versa. A CQI for a given channel can be computed by making use of a performance metric, such as a signal-to-noise ratio (SNR) or signal-to-interference plus noise ratio (SINR) [3].

Tab.1. Adaptive modulation and coding scheme (AMC) for LTE standard [3].

channel quality index (CQI)	**OFDM subchanels signaling scheme**	**code rate (code word length = 1024)**
1	QPSK	78
2	QPSK	120
3	QPSK	193
4	QPSK	308
5	QPSK	449
6	QPSK	602
7	16QAM	378
8	16QAM	490
9	16QAM	616
10	64QAM	466
11	64QAM	567
12	64QAM	666
13	64QAM	772
14	64QAM	873
15	64QAM	948

In the case of UAC systems the SNR or SINR as the instantaneous CSI, useful for the physical layer optimization, is not satisfactory. Other phenomena than noise are significant, with the Doppler effect at the top of the list. The instantaneous channel impulse response measurements are needed in order to determine the current values of parameters such as delay spread, Doppler spread, coherence bandwidth and coherence time. These parameters, being a part of the statistical CSI in the case of radio systems, should be measured during the UAC data transmission to adjust the physical layer parameters in response to the variation of the underwater channel conditions.

In modern radio systems the knowledge of the channel statistics determines the OFDM technique being applied to the signals transmitted through the time-varying multipath channels. The physical layer parameters such as the subcarrier spacing or symbol duration eare selected on the basis of standard propagation models. Moreover, complex channel coding techniques are implemented, such as turbo coding and low-density parity-check codes (LDPC). The instantaneous CSI, represented by the CQI, determines the digital modulation signaling scheme in OFDM subchannels and the channel coding redundancy [3]. Table 1 shows these relationships for the LTE standard.

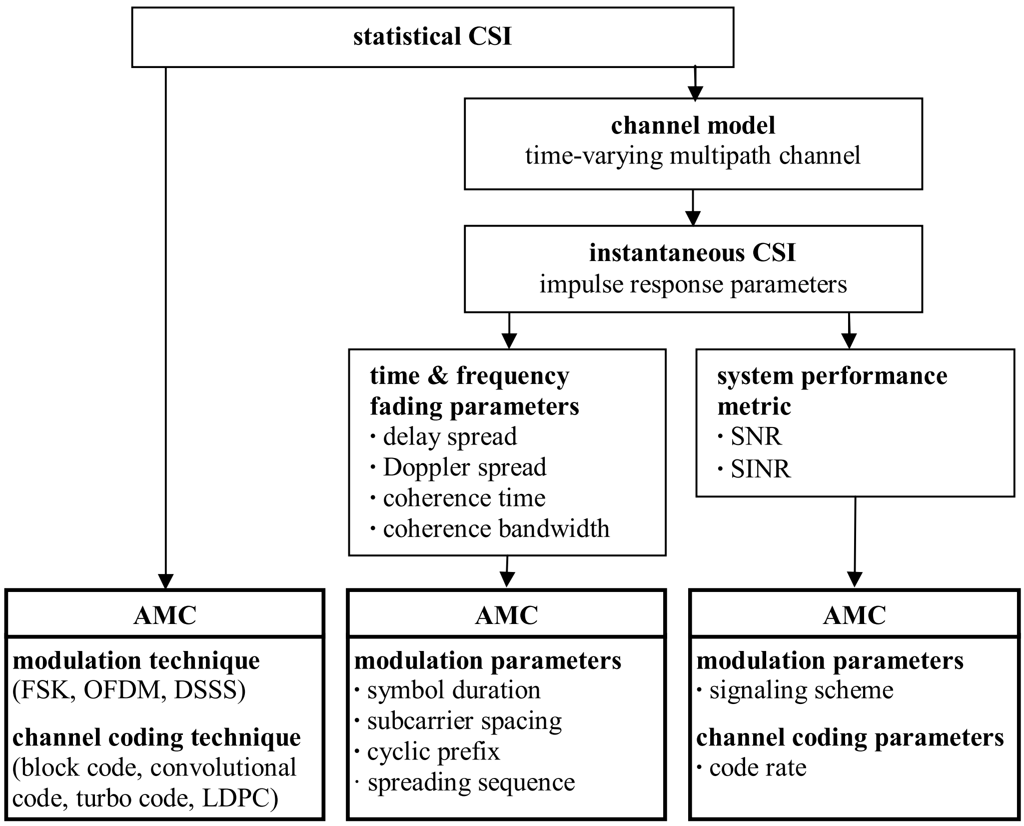

Fig. 1. Adaptive modulation and coding (AMC) for underwater communication system.

In contrast to modern radio standards, which aim to realize high-speed data with the assumed bit error rate (BER), the requirements imposed on the communication UAC are diverse, thus different modulation and coding techniques should be chosen. When a high-rate video transmission is the priority, the OFDM technique should be implemented, similarly as in the case of radio systems. In the case of high-rate and reliable measurement data transmission the OFDM technique combined with the channel coding and interleaving, matched to the error statistic, should be applied. Finally, when the reliability of the control signals transmission is the priority, the direct spread spectrum technique (DSSS) combined with the channel coding and interleaving should be implemented. The possibility of the use of complex coding techniques such as turbo coding or LDPC should be considered as a trade-off between system error performance and the computational complexity introducing a time delay in signal processing path both in the transmitter and the receiver of the UAC system.

The detailed physical layer parameters such as OFDM subcarrier spacing, symbol duration, cyclic prefix duration or the DSSS spreading sequence length should be chosen based on the instantaneous CSI measurement. On the other hand the OFDM subcarriers signaling scheme or the code rate may be matched to the one of the system performance metrics (SNR, SINR), as in the case of modern radio standards. Figure 1 shows the proposed procedure for matching the modulation and coding parameters to the channel state information for UAC system.

The underwater channel impulse response measurements should be conducted as often as necessary, with a sufficient time resolution. In order to estimate the channel characteristics, the channel needs to be sounded with a broadband excitation signal, the autocorrelation function of which should be as similar to the Dirac delta impulse as possible. Moreover, the signal should be immune to various kinds of noise and the deconvolution technique used in the estimation has to maximize the SNR of measured channel impulse responses. These requirements determine the choice of MLS signals [2].

2. DESIGNING

The concept of an adaptive system, inspired by modern radio communication standards, requires the development of metrics equivalent to the radio channel quality index. The basis for its development could be the parameterized description of the channel impulse response, taking into account the delay spread, Doppler spread, coherence time and coherence bandwidth. The system quality performance metric, such as SNR and SINR could be the additional CQI, determining the details of the data transmission physical layer. Figure 2 shows a schematic diagram of the physical layer of adaptive digital communication system being an extension of a classical system [1].

In [2] the impulse response measurements and communications tests are described, conducted with the use of a laboratory model of an OFDM data transmission system in both static and moving configurations of a receiver, first, in a reverberant air-acoustic channel and, second, in a shallow lake. The tests have shown that there is a relationship between the WSSUS parameters of the underwater channel and the OFDM subcarrier spacing efficiency. Moreover, the simulations conducted with the use of data measured in a shallow lake have shown that in a particularly tough channel the channel coding with sufficient redundancy allows for any, even very slow, communications.

The transmission signal bandwidth and synchronization technique should be invariant parameters of the physical layer of the transmission protocol. The synchronization technique should be immune to strong multipath propagation and Doppler effect. In [2] promising results were obtained using the maximum length sequences.

The majority of underwater acoustic channels are characterized by a poor quality physical link, caused by time-varying multipath propagation and motion-induced Doppler distortion. The bit error rate (BER) of an acoustic link can vary with time as the propagation conditions change. The UAC in such channels requires a well-designed data link layer of the transmission protocol. The handshake procedure should include the instantaneous CSI measurement, the range testing and the physical layer parameters negotiation. A proposal for a handshake procedure for adaptive OFDM system is presented in [4]. On the other hand in case of military AUVs data link layer of transmission protocol should be consistent with STANAG 7085 standard.

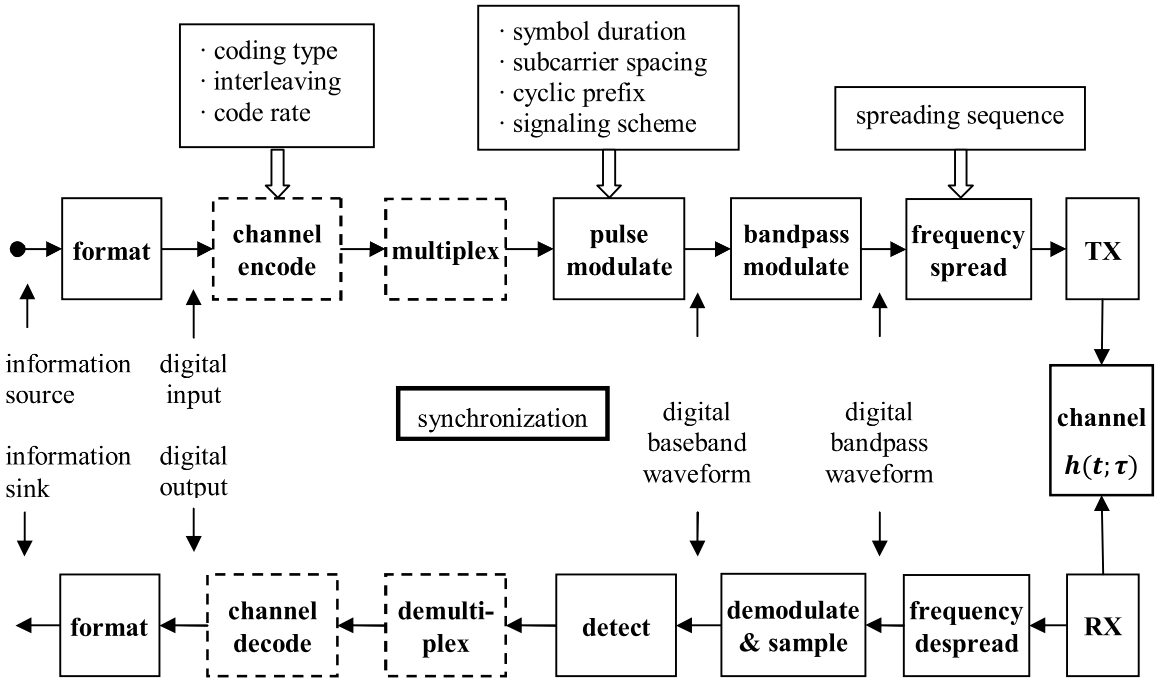

Fig. 2. Schematic diagram of physical layer of adaptive digital communication system.

Another problem to be solved is beyond the conception of the handshake repeating rate. It should take place every time the DLC, ATAC or AUV working scenario is being modified, but also when the underwater channel propagation conditions significantly change. A significant change of the UAC channel properties can be identified on the basis of the system performance metric, i.e. bit error rate (BER).

In poor quality physical links an automatic repeat request (ARQ) procedure should be implemented, to enable erroneously received data packets to be retransmitted. In modern radio systems the hybrid ARQ (HARQ) technique is used. Seaweb acoustic communication and navigation networks implement the selective ARQ [5].

There are existing commercial off-the-shelf (COTS) underwater modems, ready to be installed in underwater communication systems. The devices are supplied by manufacturers such as: Linkquest, EvoLogics and DSPComm. However, none of the manufacturers offer an adaptive solution. Thus, the self-construction of the modem may be inevitable for adaptive UAC systems designers. Reconfigurable systems (e.g.FPGAs) are a class of computing architectures that allow tradeoffs between flexibility and performance. They provide the performance needed to process complex digital signal processing applications and especially provide increased performance benefits for highly parallel algorithms. Furthermore, they are programmable, allowing the same device to be used to implement a variety of different communication protocols. In [6] a FSK underwater modem is described. All the digital signal processing and control required for the modem was implemented with the FPGA. The low cost of the hardware, compared with commercial modems, is underlined as the main advantage of such a solution.

Also modular solutions for wireless systems can be used in the UAC system hardware design stage. On the market there are COTS components implementing the OFDM and channel coding techniques [7] for wireless communication systems. Some of them could be used in a UAC transmitter and receiver, as computationally efficient, ready-made solutions. The implementation of selected techniques, using these specialized arrangements, should take place after a series of tests that verify the accuracy of the physical and data link layers concept of the UAC system transmission protocol.

3. VERIFICATION AND TESTING

The adaptive UAC system elements concept and design verification should be conducted in several stages (figure 3).

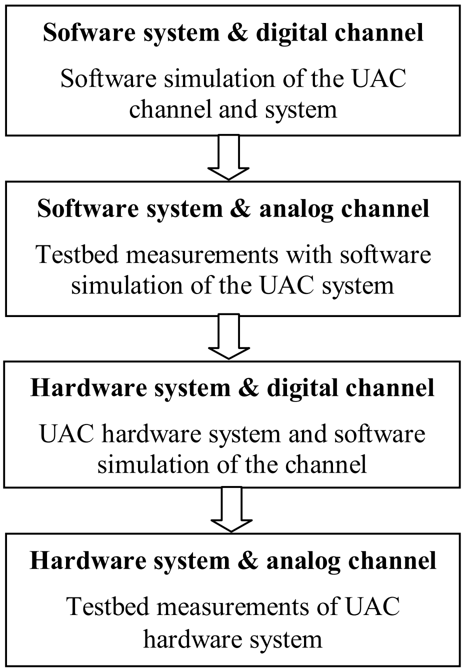

Fig. 3. Verification stages of the adaptive UAC system elements concept and design.

The first stage is the software simulation of the UAC channel and the elements of an adaptive system transceiver and receiver. The development and verification of signal processing algorithms requires a realistic and flexible simulation environment. While the research in radio communications is mostly based on simulations using established propagation models, the research in UAC is mostly based on sea trials: expensive, time-consuming, and weather dependent. The world studies include the research and construction of UAC channel simulators; however the results of measurements are not shared in a form suitable for data transmission physical layer designing [8]. The development of a statistical CSI description for different classes of underwater channels requires numerous impulse response measurements in different reservoirs and weather conditions. An impulse responses database may form the basis of the information system available to the scientific community to develop models of communication channels as well as to engineers for testing UAC systems in simulations based on real impulse responses.

The next step of the UAC system testing procedure should be testbed measurements with the use of a software simulator of the transmitter and the receiver signal processing functionality, allowing for initial testing of the transmission signals performance in a real environment. The A/C and C/A processing problems should be identified and resolved at this stage. Also, the data transmission synchronization algorithms should be verified, which is not possible in the software-only stage 1 of testing procedure. The transmitter and receiver simulators should be clearly separated as independent computers with A/C and C/A converters, signal amplifiers and hydroacoustic transducers.

After the signal processing algorithms verification, the hardware modules should be tested. Due to the lower organizational and financial costs, the preliminary tests could be conducted with the use of a UAC channel software simulator. For this purpose, the measured real impulse responses should be used. In this case the real analog signals would be processed by the digital channel simulator.

The last stage is the real environment testing of the hardware UAC modems, conducted in different reservoirs and weather conditions.

4. CONCLUSIONS

The DLCs and the ATACs, as well as the AUVs, use acoustic links in different environmental conditions; thus there is a diversity of underwater acoustic channels. The physical layer of the UAC protocol should adapt to varying channel transmission properties.

The design methodology of the adaptive acoustic links working in any propagation conditions should take advantage of the experience of modern radio standards. The real environment experiments should be preceded by tests conducted under laboratory conditions, using both the software simulators and the hardware components. The UAC channel simulator should be constructed on the basis of the real underwater channel impulse responses; thus there is a need to gather data from numerous measurement sessions in different reservoirs.

Comparing the results of each testing procedure stage should provide knowledge about the validation possibilities of the UAC system performance in test environments combining "natural" analog elements and digital software simulations.

REFERENCES

[1] B. Sklar, Digital Communications: Fundamentals and Applications (2nd Edition), Prentice-Hall, pp. 944-996, 2001.

[2] I. Kochanska, H. Lasota, Investigation of underwater channel time-variabiliy influence on the throughput of OFDM data transmission system, POMA, vol. 17, pp. 070048, 2012.

[3] 3GPP TS 36.201, Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Physical Layer - General Description.

[4] I. Kochanska, H. Lasota, Application of OFDM technique to underwater acoustic data transmission, Hydroacoustics, vol. 14, pp. 91-98, 2011.

[5] J. Rice, Seaweb acoustic communication and navigation networks, Underwater Acoustic Measurements: Technologies & Results, Heraklion, Crete, Greece, 2005.

[6] B. Benson, Ying Li, B. Faunce, K. Domond, D. Kimball, C. Schurgers, R. Kastner, Design of a Low-Cost Underwater Acoustic Modem, IEEE Embeded Systems Letters, Vol. 2, No. 3, pp. 58-61, 2010.

[7] http://www.aha.com/index.php/resources/product-briefs/

[8] R. Otnes, T. Jenserud, J. E. Voldhaug, C. Solberg, A roadmap to ubiquitous underwater acoustic communications and networking, Third International Conference on Underwater Acoustic Measurements, Technologies and Results, Nafplion, Greece, 2009.