

BURST COMMUNICATION – A SOLUTION FOR THE UNDERWATER INFORMATION MANAGEMENT

IVOR NISSEN

German Technical Center for Ships and Naval Weapons, Naval Technology and Research (WTD 71), Research Department for Underwater Acoustics and Marine Geophysics (FWG), Kiel, Germany, IvorNissen@Bundeswehr.org

The performance of collaborating information systems in the hydrosphere is based on the robustness and tolerance of the wireless communication task. It is strongly intertwined with the cooperation and coordination reliability under water for sharing resources and common purposes. Key technology and bottleneck is the physical layer communication in the underwater 'chameleon' acoustic channel environment and the challenges of non trivial channel effects like the multipath propagation - which is rapidly varying over time and space. In this contribution we introduce the burst communication as one possible solution. These transmissions are supposed to be of a very short duration. The purpose is to occupy the acoustical channel in the underwater column only for a short time window, like in impulse and click communication (similar to the use by marine mammal, Khoisan and wugbe languages), e.g. to reduce the probability of transmission collisions and allows an efficient Emission CONtrol (EMCON).

INTRODUCTION

It is well known, that wireless ranges for underwater communication over more than 100 meters can only be reached by the use of hydroacoustics. Furthermore, it is a standard procedure to use avoidance techniques for doubly spread channel effects, the spread of the transmitted signals in the time and in the frequency domain. But it is not a simple task to determinate optimal parameter settings - without this step it is not only inefficient also unreliable. On the other hand, whales, dolphins and some fishes are using acoustical signals successfully - mostly in click communication - in the noise-superimposed multipath and multi-Doppler environment; carrying the information in the click sequence and pattern. The crucial question is, can we learn from them to improve our communication systems to a cognitive radio?

1. THE ACOUSTICAL 'CHAMELEON' CHANNEL

Since 2001 FWG has been measuring and collecting sound channel probes in different ocean areas. One important result of a clustering of the spread identification triple (excess delay spread, Doppler power spectrum spread and roughness of Bello's scattering function) of the channels is, that spread in time delays is orders of magnitude higher than in frequency. The multi-path propagation with a varying sound speed in space and time results in a diversity of Doppler shifts (Figure 1). Contrary to the use in COST 207 models (*European Cooperation in Scientific and Technical Research project 1984-1988*), the underwater measurements reveal no clusters, no typical situations with sharp boundaries like bad archipelago, "rural" shallow water, "good weather", etc..

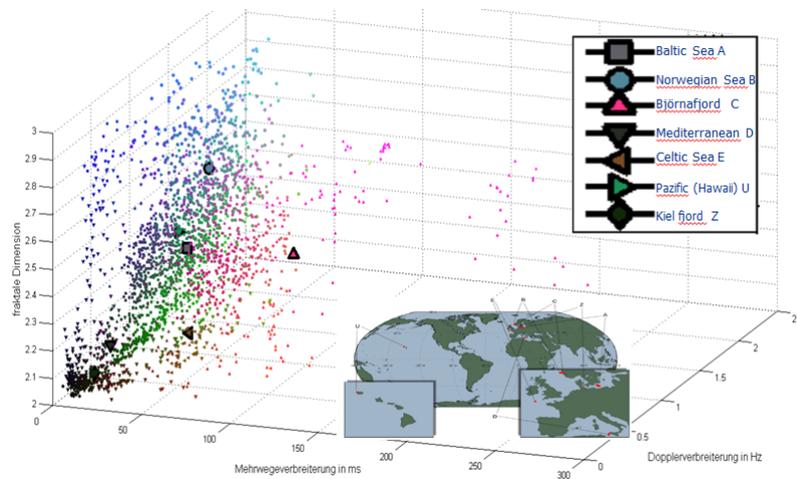


Fig. 1: A clustering based on [1] of 2336 out of 3500 analyzed FWG-measurements since 2001 measured 30 s -impulse sequences by the channel color. A significant spread in time scale compared to the Doppler scale is noticeable. Maximum measured time spreads of 1.3 seconds are not displayed, the Doppler spread is here limited by 4 Hz.

A channel displaying both time-delay and frequency dispersion is known as a doubly spread channel. If the product of delay spread and Doppler spread exceeds unity, then the channel is known as being overspread. Reliable communication in this case is a challenge. In the light of a robust event-based approach, the application and the scenario lead to consequences for the design of cognitive communication systems.

2. ADAPTIVE SOLUTIONS

Since the turn of the Millennium many authors are discussing adaptive receiver and transmitter structures. In practical applications, the channel impulse response is not known a priori and especially its length has to be estimated prior to further channel identification/equalization. Therefore, a common approach is to apply information theory methods for the identification of in situ underwater channels, namely *Akaike's Information-Criterion* (AIC), *Minimum Description Length* (MDL) and the Kolmogorov complexity.

The adaptive OFDM-System MUWACS (*Mobile UnderWater Acoustic Communication System*) with optimal parameter choices was proposed in [2]. The introduced parameter hedgehog for multi carrier communication systems is given by

- the mapping factor, 2-PSK to 16-QAM
- the code rate, FEC, taps, ...
- number of sub carriers,
- guard spaces in time and frequency domain,
- pilot number and pilot pattern, collected in Figure 2.

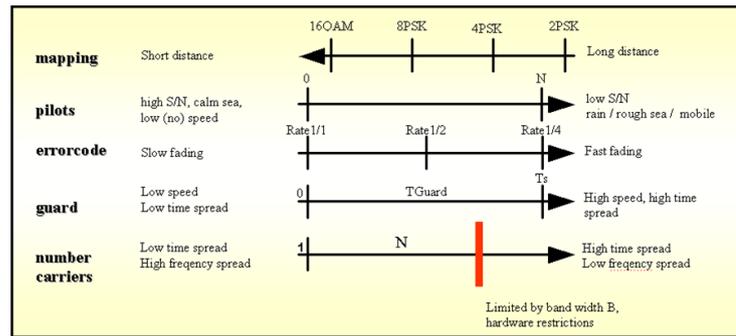


Fig. 2: The choice of optimal parameters in the multi-carrier MUWACS, based on [2].

The latter use of the pilot pattern, to estimate the transfer function in situ, is part of a cognitive radio [3]. Prefix methodes using a priori measurements are described in [4]. This is another purpose of the synchronization preamble and it allows initial channel estimation and Doppler compensations. But the question is, is it possible to adapt and track the fast varying channel? Is a cognitive system for underwater issues only an unrealizable wish? For example, in a half duplex situation for a Selective Repeat Request (SRQ) mechanism for reliable data transmission the same situation as in time reversal approaches occurs: After the channel impulse response measurement stage is completed, the channel properties have changed. Due to the low velocity of the acoustic carrier wave and the long propagation delay ($10km \approx 6.5s$), the transmitter receives outdated information, which are not useful for the next transmission. A guard time interval larger as the excess delay spread reduces the possible data rate, a shorter interval increases the equalizer effort.

In the following, with the knowledge of Section 1 and 2 we restrict the duration of the transmissions of a single symbol:

3. UNDERWATER BURST-COMMUNICATION

The idea behind a burst-beacon [5] is to transmit only a single symbol over the maximal given bandwidth in a short duration, a completely opposite approach compared to the frequency hopping strategy used e.g. in JANUS [6]. With the transmission of only one symbol no *Inter-Symbol-Interference* (ISI) occurs and the receiver only has to compensate the *Co-Symbol Interference* (CSI), also known as *Self-Symbol Interference* (SSI), that originates as a consequence of underwater multipath propagation, illustrated in Figure 3.

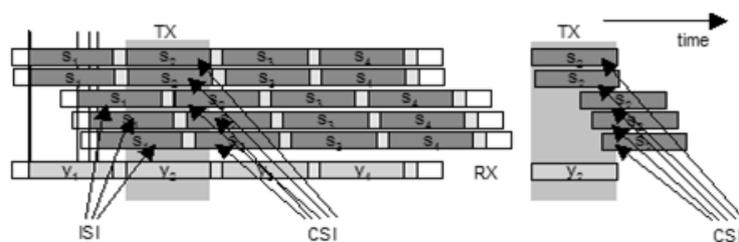


Fig. 3: Multipath environment with left: many symbols s separated by too small guard times and occurrence of ISI in the received symbols y , and right: one single communication symbol (burst) without ISI and without the estimation of a guard time interval.

By CSI/SSI is meant the reception of multiple echoes of the same signal within the symbol duration, in contrast to ISI which means that echoes are interfering with following symbols. The most difficult adaptive parameter is the guard time interval between symbols, like a cycle prefix. It depends and has to be estimated from the given multipath environment. For the use of bursts a guard time interval is not needed. With only one symbol dealing with time spacing becomes unnecessary.

The drawback using bursts is the limit to data transfer volume, as each transmitted symbol must have a limited length. In the next paragraphs one realization form and the advantages of using bursts are described:

- No spread of symbols in time (since only one symbol, no ISI, only CSI),
- Low spread of energy over time (receiver friendly, higher SNR),
- Covertness (intercept unfriendly)
- Low energy consumption (power of endurance, sustainability),
- Low duty cycle (transducer friendly),
- Less stress for others (marine mammal friendly, lower *Sound Exposure Level*),
- Fewer collisions in networks (network friendly),
- Utilization of the multi path environment (orientation friendly)

Here higher SNR means the *Signal-to-Noise Ratio* (SNR), described in the context of the sections Covertness and EMCON.

3.1 REALISATION OF A BURST

One example of a burst communication realization is the *Transient Underwater Acoustical Communication System* (TUWACS) developed by FWG. It is based on *Filtered Multi-Tone* Modulation (FMT) [5] and uses bursts in a frequency band from 3.5 - 8 kHz. TUWACS transmits a single symbol of 128 bits in a short burst of about 250 milliseconds. Ten additional bits can be included in the pilot block of the symbol. The comparatively short transmission time reduces the packet collision probability, which is crucial in a full ad-hoc network with a shared medium. More importantly, it reduces the energy over time, the processing power and increases the possibility to create a slow fading channel. TUWACS was implemented in its incoherent form in the ELAC underwater telephone UT3000 and in its coherent form in modems from Develogic [7, 8] and SAAB, making them interoperable in sea trials. A detailed list of all properties of TUWACS is given in Table 1.

3.1.1 Channel coding

Common codes in underwater acoustic communication are convolutional [2, 9], Bose-Chaudhuri-Hocquenghem- (BCH) [10] and concatenated convolution codes like turbo [11, 29] or *Low Density Parity Check* (LDPC) codes [12, 13], which are well-known from terrestrial communication. The channel decoding of concatenated coding schemes is usually done in an iterative decoder where 'soft information' about the systematic bits is exchanged between the constituent decoders or the decoder and the equalizer in case of turbo equalization [9]. This soft information, usually in the form of log-likelihood ratios

Tab. 1: Properties of the TUWACS burst physical layer communication scheme for incoherent (MFSK) and coherent (μ PSK) modulation

Sampling rate	36,000 Hz
Frequency band	3,500-8,000 Hz
Bandwidth	4,500 Hz
Transmission time	≈ 250 ms
Payload (netto)	128 + 10 bits/packet
Data rate (netto)	70 byte/s
Acoustic Link (here with QPSK)	1969 bits/s
Efficiency	12.5% bits/Hz

(LLR), provides the other decoder in the next iteration with reliability information about the bits, it improves the decoding quality using the extrinsic information gathered in the previous decoding stage [14]. This, of course, implies that the higher layer protocols are also able to process the soft information, for instance in form of a reliability value $\in [0, 1]$. At the end of the iterative decoding process this value represents the integrity of the data volume without evaluation of the content, e.g. a possible checksum, for cross-layer approaches, [15].

For burst communication we assume that only a small user volume, say e.g. 128 bits, needs to be (channel) encoded and we assume a small amount of total transfer data volume. The corresponding small amount of coding bits is not optimal for achieving high coding gains with powerful codes like LDPC or turbo codes which are usually based on long word lengths (from around 1000 to several ten thousands [16]). The question arises, which codes are applicable for burst communication. In [17] different burst coding methods are presented and discussed. Turbo codes are a good choice (see Figure 4), but the necessary processing power for the complex scheme is higher compared to the convolutional codes.

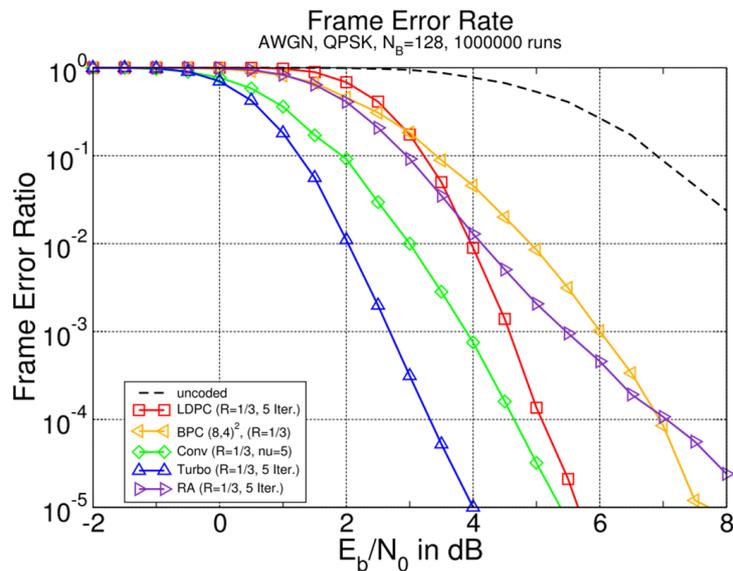


Fig. 4: Frame error rate in a AWGN channel (additive white Gaussian noise) for different burst coding methods with 128 Infobits and QPSK mapping. Turbo codes scores well (blue line), based on [17].

3.1.2 Mapping

For higher spectral efficiency, a higher-order modulation scheme is desirable compared to MFSK, like phase-shift keying variants (BPSK, QPSK, μ PSK) or, with strong restrictions, quadrature amplitude modulation techniques (μ QAM). Clearly, the larger the constellation size, the more the *Bit Error Rate* (BER) will rise since the constellation points get closer together and noise and interference will cause more erroneous decisions. Most common QPSK mapping for underwater communication is used, e.g. in [2, 10]. But also higher order mappings were published, like 16QAM in [2, 13] and up to 64QAM in [12]. The BER vs. SNR performance of a differentially-coherent scheme is slightly worse than a purely coherent scheme with perfect synchronization, but in case of blind channel estimation (vertical channel) the differential mapping is still a good choice. In adaptive approaches the μ -selection in a given mapping class is the most efficient parameter ($\mu \in \{2^0:\text{MFSK}, 2^1:\text{BPSK}, 2^2:\text{QPSK}, 2^3:\text{8-PSK}\}$), based on Figure 2.

3.1.3 Modulation

A higher efficiency, that cannot be reached with traditional incoherent modulation schemes like frequency-hopping, is desirable. For optimal utilization of the available bandwidth by a high spectral containment, multicarrier systems, especially in form of orthogonal frequency-division multiplexing (OFDM), are widely used. Under water these were already presented, e.g. by [4]; first successfully demonstrated for broadcast long range communication to a submarine with MUWACS in 2002 [2] and in the UCAC project as described in detail in [23]. An important issue with OFDM is to maintain the orthogonality of the subcarriers which are corrupted due to the Doppler effect within the channel. Therefore, methods for Doppler estimation and compensation have to be employed. The great advantage of OFDM is the reduced effort needed for equalization.

The Generic Modulation Scheme (GMS) [18] for band-pass, multi-carrier, frequency-hopping, pulse-shaped signals result in a flexible modulation named Filtered Multi-Tone (FMT). In the case of only a single symbol the GMS simplified to the equation (1)

$$s(t) = \text{Re} \left(\sum_{\mu=0}^{N_{\text{Carriers}}-1} c_{\mu} g(t) e^{2\pi i f_{\mu} t} \right); t \in [0, \dots, T_S]. \quad (1)$$

The equation represents the Generic Modulation Scheme (GMS) for the bandpass time signal s for one symbol, with the carrier-number, hopping carrier frequencies f_{μ} , the elementary pulse shape g , the fixed sub-symbol chip duration time T_S , and the mapping values c generating common adaptive waves. Not seeking orthogonality among subcarriers, there are similar designs using different pulse-shaping filters (*Discrete Multi-Tone* DMT/OFDM can be considered as a special case by using a rectangular pulse) and hence, employing a more general multi-carrier modulation scheme [18] like FMT. Due to the possible overlap in time and/or frequency, interference is induced. To mitigate this, a more sophisticated equalizer is necessary. A realization of the filtered multi-tone modulation using raised-cosine pulses and decision-feedback equalization is described in [19]. TUWACS is using FMT modulation with the freedom of the carrier number depending on the device capabilities and the pulse shape g , depending on the SNR-Doppler-situation for an

adaptive behavior. At the end of the modulation step a clipping of 2–3% produce a crest factor gain of more than $3dB$.

3.1.4 Synchronization

The most critical point in every communication system is the synchronization in time as well as in frequency. For time synchronization, a common method is to make use of frequency-modulated waveforms (chirps) as a preamble before the data symbols. The receiver correlates the received samples with a local replica to estimate the beginning of the transmission. In OFDM systems using a cyclic prefix, this can be used for fine symbol synchronization, since it introduces additional redundancy in a regular pattern to the symbol in a defined way. The single burst symbol do not employ an additional preamble to extend the time signal. Their realtime detection is achieved via a coarse and a fine synchronization step, e.g. based on a pilot block “header” in the frequency band followed by the iterative turbo decoded modulated signals, using pilots on all odd carriers and data on even carriers. The pilot pattern is also an adaptive parameter for synchronization and channel estimation.

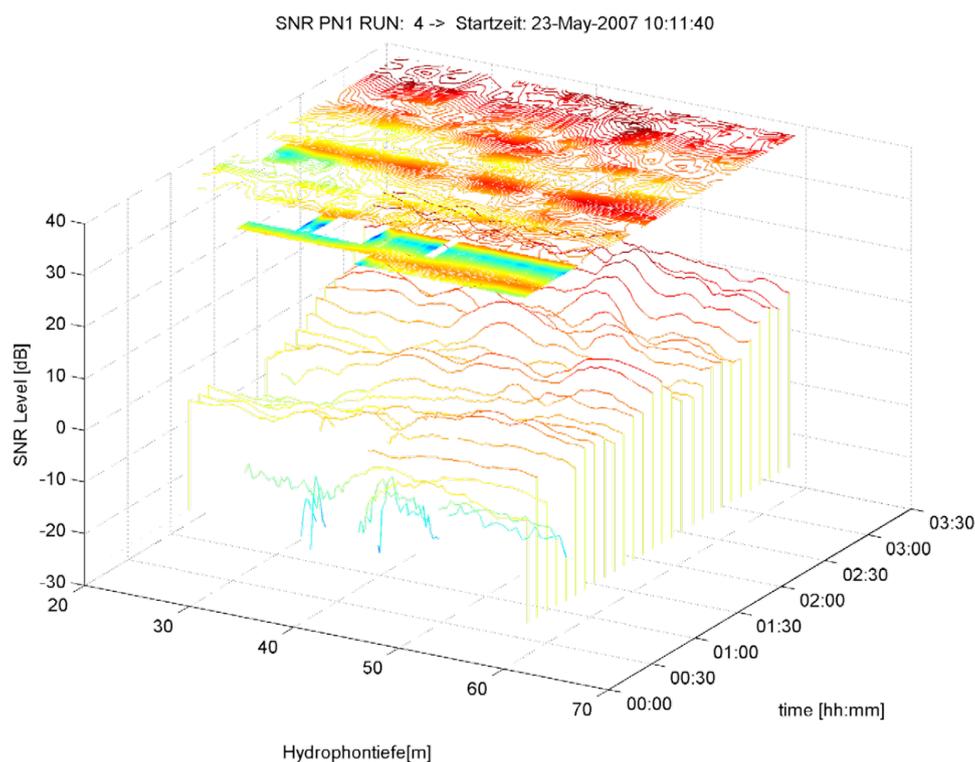


Fig. 5: Signal Excess (SE) in range (\approx time) and depth of a sea experiment in the Mediterranean Sea in 2007 (CCUP07) with best weather conditions. A towed transducer (5 kn) is transmitting over three hours to a receiver chain with 128 hydrophones in the water column. The individual SNR as sum of SE and detection threshold ($DT = 0$) is a function of the transmission loss and the ambient noise of each received signal was plotted. Some positions in the water column (Latitude, Longitude, depths) far away have a higher SNR compared near by, the function is strongly nonlinear.

3.2 Covertness and EMCON

It is possible to define the word 'covertness' for communication systems, in the sense of a *Low Probability of Detection* (LPD) by uncooperative interceptors. For this a communication preamble frame with a high correlation value for the synchronization should be avoided. The signal is said to be covert to the interceptor, if the SNR in the signal bandwidth is lower than a threshold value at the interceptor as a sum of Signal Excess $SE_{\text{Interceptor}} := SL_{\text{Transmitter}} - TL_{\text{Transmitter} \rightarrow \text{Interceptor}} - NL_{\text{Interceptor}} + DI_{\text{Interceptor}}$. A low SNR serves to deter unwanted listeners to detect the presence of the transmitted signal, but it is not trivial task to calculate the signal excess at the interceptor position, same with distance circles. In Figure 5 the SNR = SE(DT=0) in different ranges and depths are shown. A solution is, to include masking into the definition of covertness. We define $\text{covertness}(\text{Signal}, \text{Interceptor}) := SE_{\text{Interceptor}} * \text{ineffectiveCamouflage} \leq 0$ with

$$\text{ineffectiveCamouflage} := \begin{cases} 1 & : \text{ if signal looks like communication;} \\ 0 & : \text{ if recognized as marine mammal signal, ship noise, ...} \end{cases}$$

and can expand this attribute to help the cooperative receiver with a higher SNR.

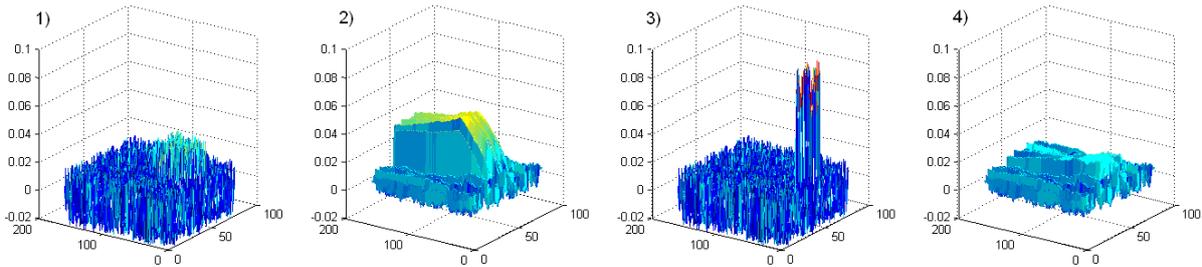


Fig. 6: 1) Spread spectrum approach expanded over time, energy under noise floor; 2) integration over time with detection; 3) burst with high energy; 4) integration with window size over the signal duration, noise included.

It is stated in [20]: “Signal detection equipment’s need time to scan, analyze and identify emissions in the spectrum, especially if these signals are spread over a large bandwidth. Short transmissions are thus more difficult to detect. Attacker never knows when the data is sent”. The integration over a given integration window length summarizes noise for short durations. For the interceptor a detection is difficult, although a helpful high SL for the cooperative receiver generates a high SNR, illustrated in Figure 6.

3.3 Marine mammal friendly

Covertness and EMCON are not only a military topic. The European Commission, Joint Research Centre Institute for Environment and Sustainability has started a long term project [21] of the registry of all loud sounds to provide an overview in the European oceans. The crucial question is: What is quiet? In the Text Box 1 “Extract of the indicators for Descriptor 11 (Noise/Energy) from EC Decision 2010/477/EU” based on Directive 2008/56/EC it was defined as: Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment. It is stated “Proportion of days and their distribution within a calendar year over areas of a determined surface, as

well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level¹ (in $dB re 1\mu Pa 2.s$ or as peak sound pressure level (in $dB re 1\mu Pa peak$) at one metre, measured over the frequency band $10Hz$ to $10kHz$ (11.1.1)” and on the next page is said “For sonar, airguns, acoustic deterrents and explosives, minimum thresholds should be used for uptake in the registers. The generic source level (SL) threshold for inclusion in the register for non-impulsive sources is $176dB re 1\mu Pa * m$, whereas the threshold for inclusion of impulsive sources is an energy source level (SL_E) of $186dB re 1\mu Pa^2 m^2 s$. For airguns and explosives it is more convenient to convert these to proxies of zero to peak source level (SL_{z-p}) and equivalent TNT charge mass (m_{TNTeq}), respectively.”

For burst communication we can assume short signal durations, e.g. $T_S = 250ms$, and an exposure “energy” level value of

$$SL_E = SL_{Burst} + 10\log_{10}(T_S) = SL_{Burst} + 10\log_{10}(0.25) < 186dB. \quad (2)$$

This (2) implies $SL_{Burst} < 186 + 6dB = 192dB$ compared to the limit of $176dB$ of communication signals of a few seconds, like UOFDM [23]. This is a gain of maximal $16dB$ in the Source Level for $250ms$. According to the above official definition bursts generate less stress for others, they have only to be registered with very high levels.

3.4 Network friendly

Cooperation and coordination as the fundament for collaborations needs networking; networking needs a reliable communication link. Underwater network protocols which have to be tolerant to long propagation delays and low flexible data rates need to be adapted to the special acoustical properties of the underwater environment, instead of adopting existing common terrestrial protocols.

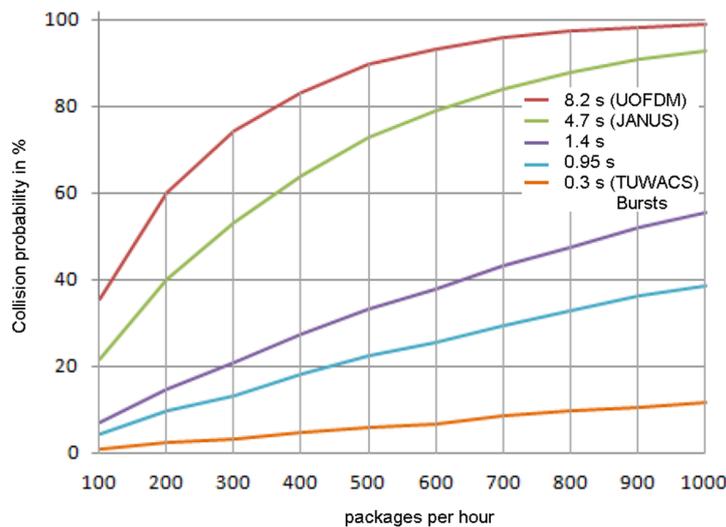


Fig. 7: Collision probability with increasing network load using different transmission durations, based on [24]

¹mistake in the document: $dB re p_{ref}^2 T : 1\mu Pa^2 s$, please compare with [22].

A simple but effective approach is to let the network node of each user in the network themselves decide the time of transmission in either a coordinated or non-coordinated fashion without carrier sensing methods. In all cases, typically a single user transmission for the multi hop will occupy the whole available bandwidth. In this time-based medium access scheme, e.g. random access protocols with many user nodes and without channel reservation, collisions are always possible, which occur when two or more communication signals arrives simultaneously at the receiver [25]. Each collision reduces the performance of the complete network (see Figure 7).

Frame- or Packet-Error-Rate (PER) simulations, which are produced to assess the impact of collisions, evaluate the function of *Signal-to-Interference-Ratio* (SIR). The overlap between desired and colliding packages in different ocean areas for different scenarios have shown an overall high interference tolerance for short bursts [26]. In Figure 7 the collision probability is plotted under a simple model assumption: every collision produces a packet error. A communication method using spread of redundancy over the time, like UOFDM [23] with large channel codes, and a following high link robustness produces a collision probability of 90% for 500 packages per hour. A burst communication with a low spread over time, shorter channel codes, and a lower link reliability shows a 7 % collision probability. A physical layer method with short transmission durations is preferable.

Mankind in its evolution has developed an economical and tolerant form of communication network protocol: gossip. Although this form with their attendant rumors is occupied negative, some areas are reliant to this communication form, e.g. the stock market. “Buy on rumors, sell on facts.” Rumors are transmitted as unconfirmed message bursts in financial centers with shortest response times acted particularly in news as a “hard facts” and influence the performance.

Rumor-Definition: A rumor is a short message burst with insecure content, source and distribution. The content of this message is not plausible assigned to a person / a communication node, but to an underlying event occurring.

The saying goes, rumors spread like wildfire, or have fast legs, rarely heard the same rumor from the same transmitter, so gossiping is a robust form for the unreliable underwater communication link. A burst cross-layer network protocol named *Gossiping in UnderWater Mobile Ad hoc NETWORKS* [27] was demonstrated with success at international sea trials in 2013 and 2014 and in simulations using TUWACS.

3.5 Orientation friendly

For localization long, short and ultra-short baseline systems are used with transmission of pings in the multi-path environment by multiple synchronous nodes. With the measured time and an adapted constant sound speed of fixed 1500 m/s relative distances are estimated, based on time difference of arrival approach (TDoA). A variety of effects complicate this determination. The sound speed is varying from approx. 1407 to 1570 m/s over space (depths) and time [18], it is unknown for the receiver. The same is valid for the actual sound energy traveled distances over the 'line of sight'-ray (especially for

convergence zones, sound channels, over bottom in shallow waters, archipelago and harbour areas, ...). In many situations it is not sufficient to know only the relative distances to a transmitting unit, however absolute coordinates are desired. The conventional 'ping', a shorttime CW-pulse, contains no information. A combination of burst communication and navigation can help in the absolute global determination, and therefore act as a kind of an "underwater GPS".

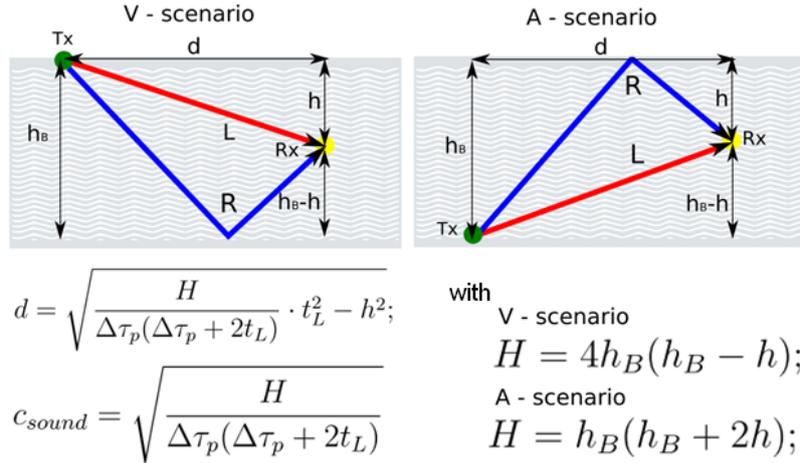


Fig. 8: The calculation of the distance for the multi-lateration process, based on [28]. Only with the knowledge of the unit and water depths and arrival time $\Delta\tau_p$ the receiver can estimate the distance d and the sound speed c_{sound} .

Given is a burst communication with the information of the transmitter position (like a lighthouse beacon) in combination with the delay of the first singular echo of the burst. With this knowledge and multi-lateration a global position and the mean sound speed can be estimated based, purely only time measurements, see Figure 8.

Due to the short transmission time it is even possible to decode echoes, for example reflections from the surface or sea floor. In Figure 10 the burst and two singular echoes is presented. The well-known spatial selectivity [29] is achieved by using adaptive or fixed receive/transmit beam patterns in beamforming. Time diversity techniques may exploit the time-based channel effects, resulting in a diversity gain, by combining multiple versions of the same signal (see Figure 9). These quasi-identical signals, which are received at different times from the same transmitter or from several relay nodes, are combined with and without channel knowledge (maximum ratio combining). The improvement compared with a single reception is known as the receive diversity gain. Additionally such echoes can be used by an *Error-Correction* (EC) layer, to cluster historical messages and to merge multiple corrupted packets into a correct one.

If a node receives multiple copies of the same message, the EC layer groups them together and tries to correct broken instances. The message may be restored by building a bitwise average, even if all received instances are corrupted. This algorithm is an innovation for networks with high bit error rates and was registered as patent in 2013 [30].

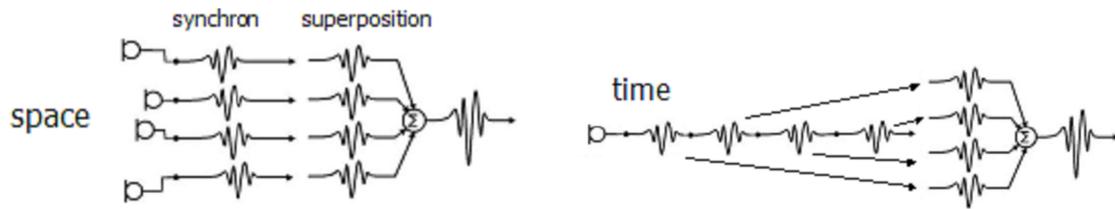


Fig. 9: Coherent combiner of several identical transmitted signals before demodulation in space (left) and time (right).

CONTENT:
 Parcel Type: Data Request
 Parcel Length: 128 Acknowledgement: NO
 Priority: LOW
 Source Address: 0.6 Destination Address: 1.0
 Data Request Type: Position
 Data Request Time: Mon Apr 14 08:43:30 2014
 Forward: YES Auto-Report: NO Periodic: NO
 Data Request Age: —
 Lat: 90 0.0000 S, Lon: 0 0.0000 E,
 Depth: 0 Validity: infinity Type Details: 0
 Checksum: 531E Checksum correct

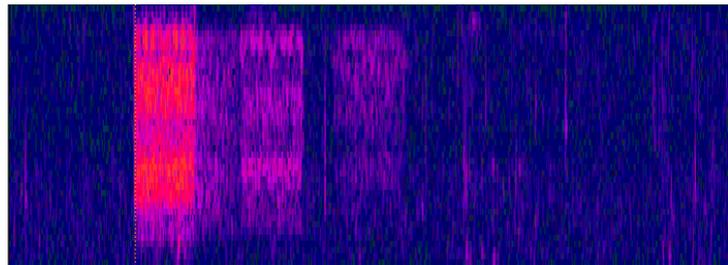


Fig. 10: Burst and two singular echoes after $\approx 450ms$; (670m) and $\approx 750ms$; (1.1km) with a position request in the Kiel harbour, burst beacon and first echo are decoded correctly.

3.6 Application

The data transfer volume in a transmission is restricted to a few bytes. Nevertheless, this is sufficient to transmit the data needed for some underwater applications, like status or detection messages, GPS positions or command and control packets.

Application examples are Identification of Friendly Submarine (IFS) or the Generic UnderWater Application Language (GUWAL); a data format for various underwater applications with 120 request groups, 120 data reply and 32 command groups, each with 32 single parcel types and a string message with 16 characters. The design concept of GUWAL is to preprocess and compress data before transmitting them over low-capacity acoustic channels. The standard packet length amounts to just 16 bytes. After the header, 96 bit data payload follow, depending on the packet and data type. At the end of each packet, a 16 bit *Cyclic Redundancy Code* (CRC) protects the integrity of the complete packet. GUWAL can be combined powerfully with beacon-files and atom-feeds using the GUWAL content as 16 byte long integer index for a link dump.

GUWAL in combination with Burst communication was demonstrated successfully within reconnaissance scenarios [26]. They were performed including stationary bottom nodes, mobile AUVs, gateway buoys and ships.

4. CONCLUSION

The burst approach provides an important technological basis for digital communication services and leads to secure network-centric scenarios for the underwater environment, which is currently not available in Europe.

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