



Gdansk University of Technology
Faculty of Electronics, Telecommunication and Informatics
Department of Marine Electronics Systems



Performance of Underwater Acoustic Channel for Communication Purposes

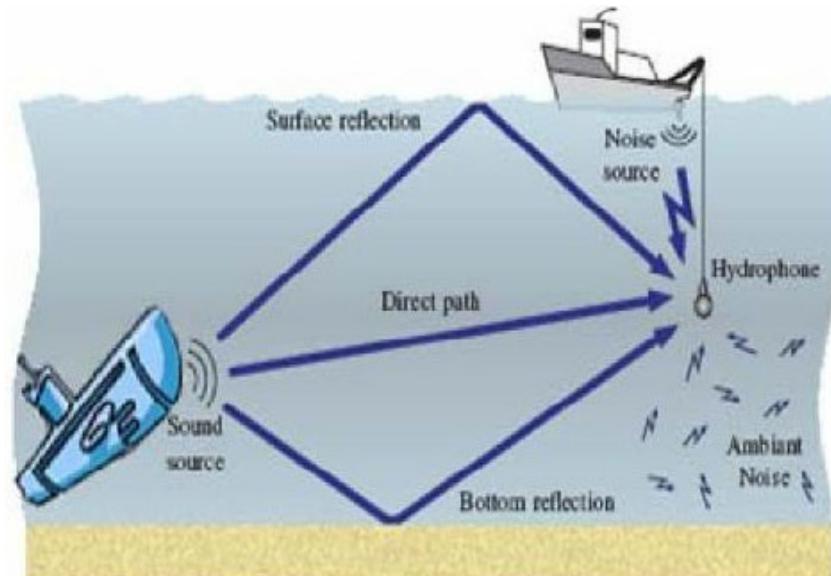
Iwona Kochańska, Jan H. Schmidt



Applications of Underwater Acoustic Communications (UAC)



- Submarine-to-submarine or submarine-to-surface platform communications
- Monitoring of bottom installations (offshore oil and gas drilling and production)
- Transmission of data accumulated by underwater platforms and vehicles
- AUV remote control
- Surveillance of certain water bodies for security and environmental monitoring
- Communication with and between manned and unmanned underwater vehicles
- Transmission of diver speech





Underwater Acoustic Communications



- UAC system **performance** is strongly related to specific propagation conditions
 - Deep water channels – up to hundreds of kbps,
 - Shallow water channels – 40-80 bps.
- Bit error rate and data transmission rate achieved in UAC systems - much lower than for wire or radio-communication systems.
 - disadvantageous **properties of the UAC channels**,
 - **technical capabilities** of the generation and reception of acoustic waves,
 - **estimation** of UAC channel transmission properties is possible within a **limited bandwidth** and with **limited temporal resolution**.

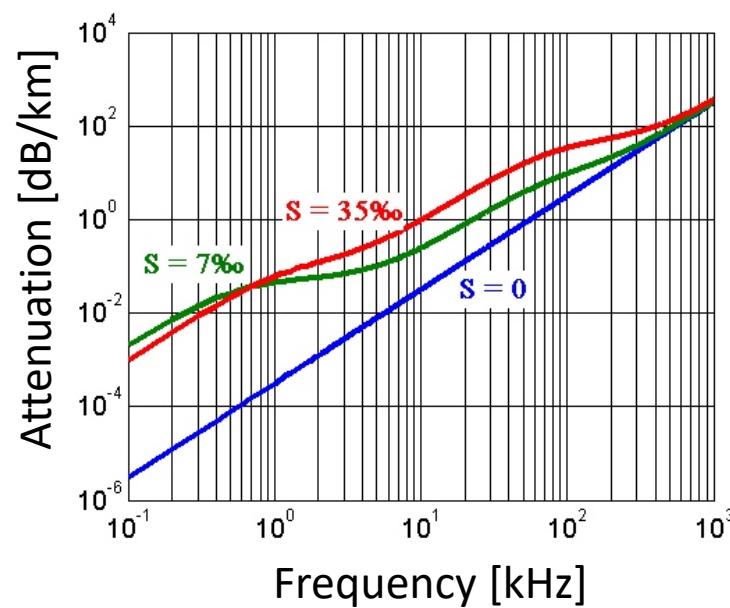


Propagation conditions: absorption attenuation



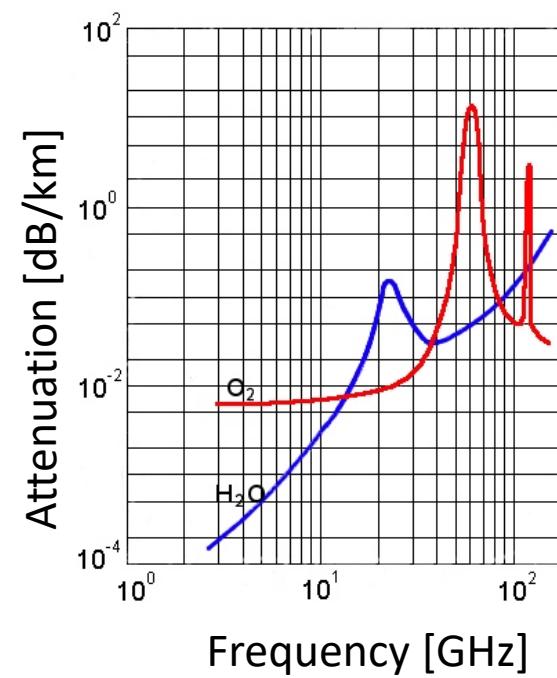
UAC

- Absorption attenuation is proportional to f^2 ; dominant influence on system range.
- Differences of attenuation limits the useful bandwidth



RADIO

Absorption attenuation is not practically relevant



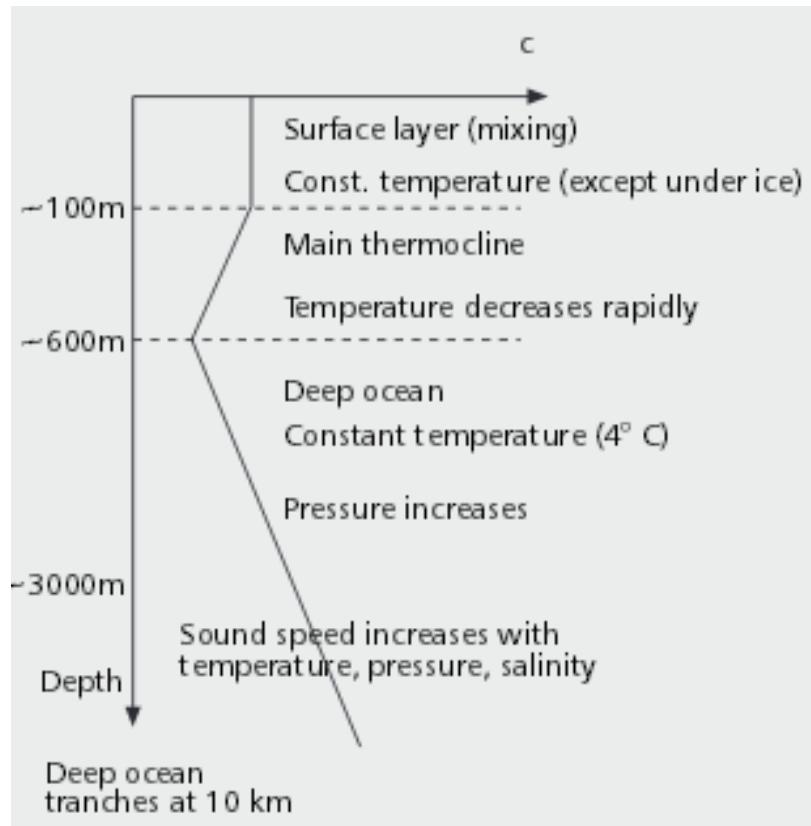


Propagation conditions: multipath propagation and refraction



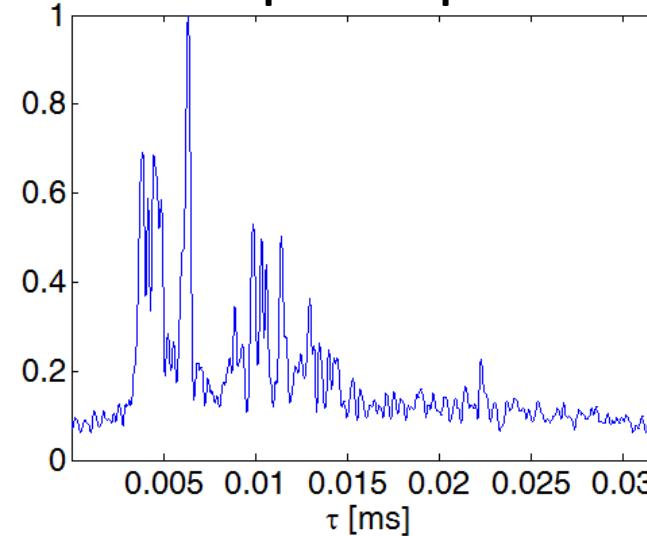
Refraction

- Speed of sound : 1450 m/s – 1545 m/s



Multipath propagation

Impulse response



- **time dispersion**
- **delay spread τ_M** – typically tens of ms
- **selective fading** in signal spectrum



Propagation conditions: time-variance and Doppler effect



Doppler effect

Parametr	WLAN	LTE	UAC
Wave speed	$3 \cdot 10^8$ m/s	$3 \cdot 10^8$ m/s	$1,5 \cdot 10^3$ m/s
Carrier freq.	2,4 GHz	2,5 GHz	10 kHz
Bandwidth BW	17 MHz	20 MHz	2 kHz
Object speed	2 m/s	36 m/s	2 m/s
Doppler shift	16 Hz $\approx 0,0001$ % of BW	300 Hz $\approx 0,0015$ % of BW	13 Hz $\approx 0,67$ % of BW

Natural time-variance of propagation conditions

Phenomenon	Period
Seasons	Months
Tides	Days/Hours
Internal waves	Minutes
Surface waves	Seconds
Microstructure	Miliseconds

Narrowband signal:

$$r(t) = \sum_n \alpha_n s(t - \tau_n(t)) e^{j2\pi v_n t}$$

Doppler spread v_M – max. Doppler shift

$r(t)$ – received signal, $s(t)$ – transmitted signal, α – attenuation, τ – delay,

n – no. reflected paths

Wideband signal:

$$r(t) = \sum_n \alpha_n \frac{1}{\sqrt{\beta_n}} s\left(\frac{t - \tau_n}{\beta_n}\right)$$

Doppler scaling factor β_M (time domain)



Designing the physical layer of data transmission



Wide-sense stationary uncorrelated scattering (WSSUS)



τ_M - Delay spread

v_M - Doppler spread (scaling factor)

B_c - Coherence bandwidth

T_c - Coherence time - the duration
for which the channel can be
considered approximately constant

$$\tau_M \sim \frac{1}{B_c}$$

$$v_M \sim \frac{1}{T_c}$$

- Time-varying impulse response $h(t, \tau)$ - a two-dimensional Gaussian processes with a zero mean
- Autocorrelation of $h(t, \tau)$:
$$R_h(t, t + \Delta t, \tau, \tau + \Delta \tau) = E\{t + \Delta t, \tau + \Delta \tau\}$$
- Under WSSUS assumption:

$$R_h(t, t + \Delta t, \tau, \tau + \Delta \tau) \xrightarrow{\text{WSSUS}} R_h\{\Delta t, \Delta \tau\}$$



Underwater Acoustics Communications

- Orthogonal Frequency-Division Multiplexing (OFDM)
- Frequency Hopping Spread Spectrum (FHSS)

What can be achieved in shallow underwater acoustic channel?

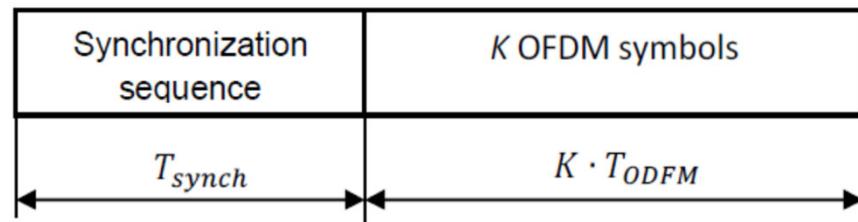
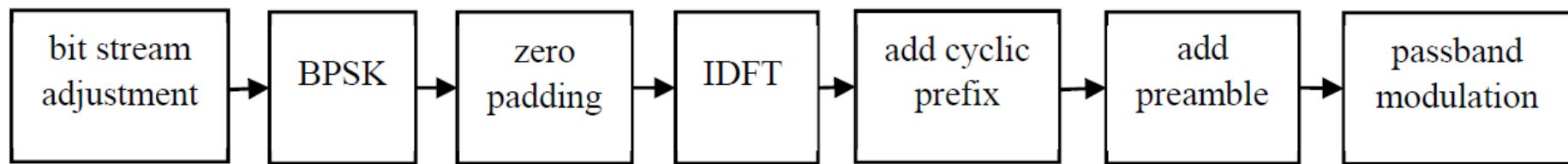
- Data transmission rate (bits per second) ?
- Reliability (bit error rate)



Orthogonal Frequency-Division Multiplexing (OFDM)



- **Orthogonal Frequency-Division Multiplexing** - the data is split into numerous parallel data streams, one for each sub-carrier, modulated with the use of a conventional modulation scheme at a low symbol rate
- Process of OFDM signal generation:



$$T_{synch} = 1.02 \text{ s}$$
$$K T_{ODFM} = 2.5 \text{ s}$$



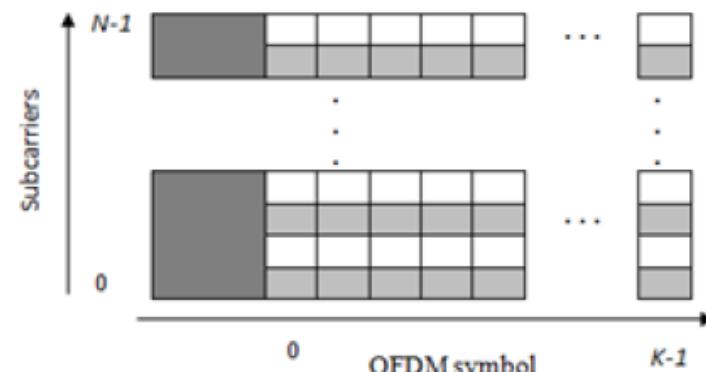
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OFDM UAC system

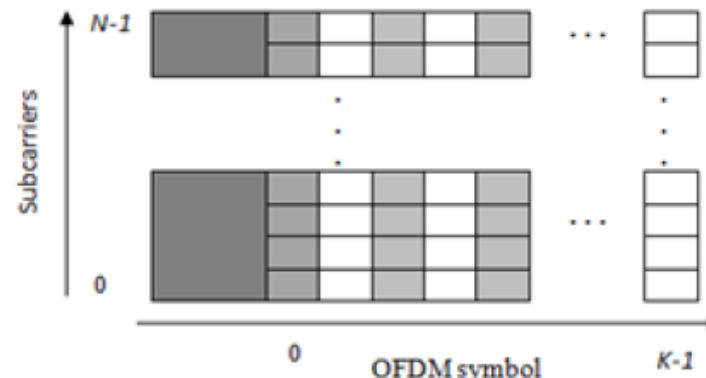


Parameter	value
Bandwidth	5 kHz
Carrier frequency	30 kHz
Sampling frequency	200 kHz
Synch. sequence	PRBS, $T_{\text{synch}}=1.02 \text{ s}$
Cyclic prefix	$\frac{1}{4}$ of OFDM symbol
Subcarrier spacing	1250 Hz, 625 Hz, 312.5 Hz, 156.3 Hz 78.12 Hz
OFDM symbol duration	0.8ms, 1.6ms, 3.21ms, 6.41ms, 12.82ms
Data transmission rate	2.84kbps (1.42kbps with PT)
Channel coding	No

Pilot tones - pattern 1



Pilot tones - pattern 2

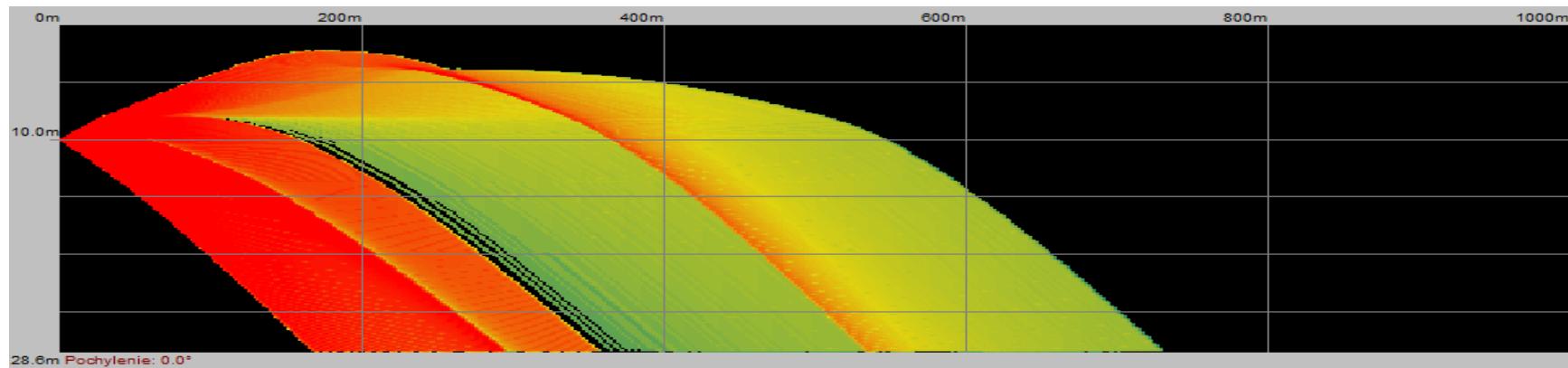
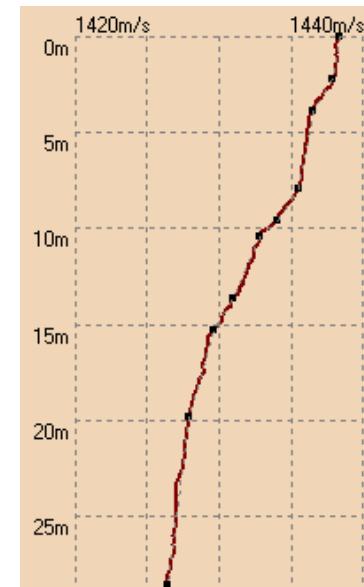




Inland water experiment, Wdzydze Lake, 4-5.05.2017



- **Hydroacoustic Research Station**
- Wdzydze Lake on the northern edge of the Bory Tucholskie forest complex ($53^{\circ}58'31''N$ $17^{\circ}54'19''E$).
- The bottom of the lake falls steeply into the depths of the water. In the shore zone, it is lined with gravel-stony material, and in the deeper parts, covered with a layer of mud.
- Experiment 1 (4.05.2017): distance 550 m; windy weather, rain.
- Experiment 2 (5.05.2017): distance 340 m and 1035 m; water surface calm; windless weather; no rain.

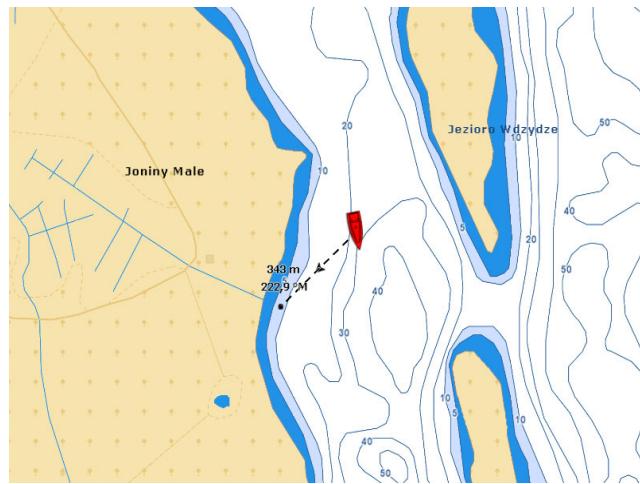




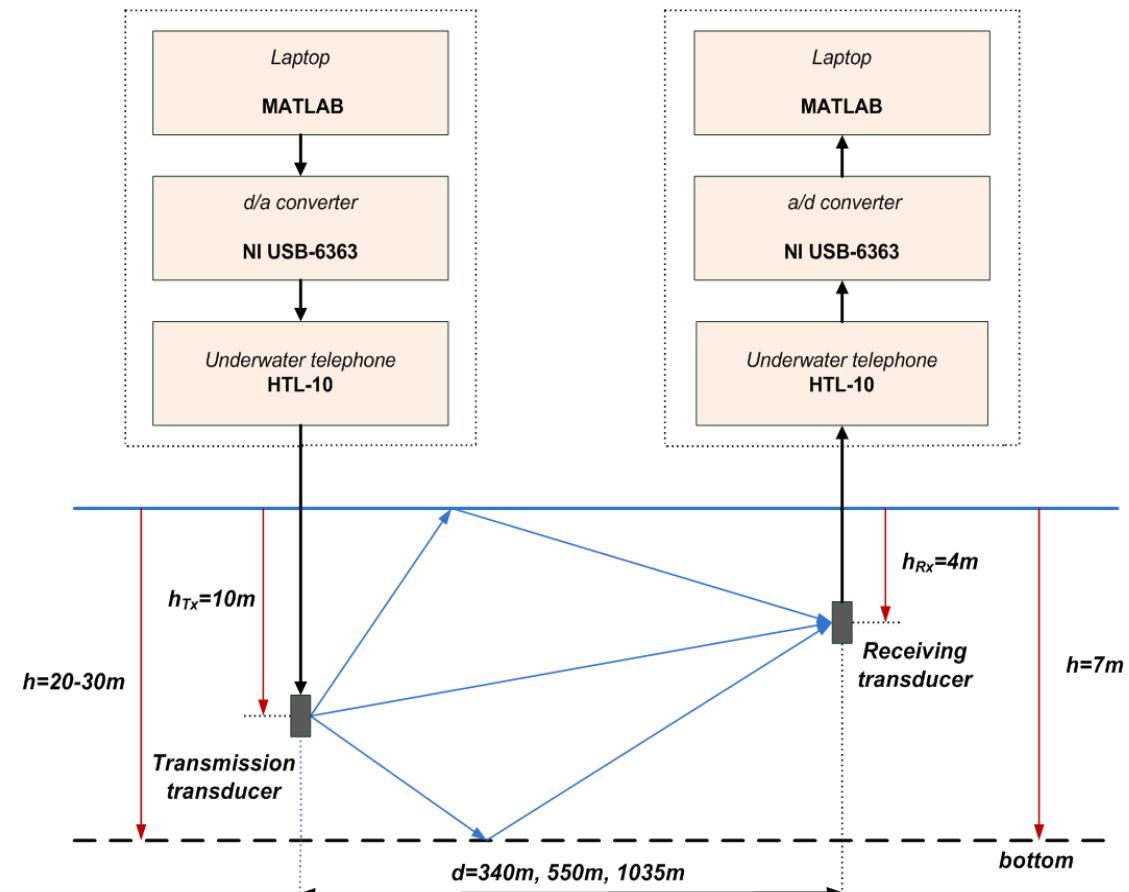
Inland water experiment: Wdzydze Lake, 5.05.2017



Wdzydze Lake



Range: 340m





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OFDM UAC system



- Inland water experiment (05.05.2017, good weather conditions, sea state 1, distance 340m)

Subcarrier spacing	BER: no pilot tones	BER: pilot tones pattern 1	BER: pilot tones pattern 2
1250 Hz	0.499	0.565	0.341
625 Hz	0.502	0.450	0.190
312.5 Hz	0.500	0.272	0.163
156.3 Hz	0.498	0.154	0.077
78.12 Hz	0.501	0.082	0.047

- How to achieve $\text{BER} < 10^{-3}$?



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OFDM UAC system



- Inland water experiment results, OFDM + channel coding
(data transmission rate without channel coding: 1420 bps)

Subcarrier spacing	BER: pilot tones pattern 1	BCH code word length	Information bits per code word	BER: pilot tones pattern 1 + BCH coding	Data transmission rate [bps]
1250 Hz	0.341	---	---	---	---
625 Hz	0.190	1023	11	6.4563e-04	15,27
312.5 Hz	0.163	1023	36	9.0519e-04	49,97
156.3 Hz	0.077	255	13	5.6749e-04	72,39
78.12 Hz	0.047	127	8	3.3706e-04	89,45

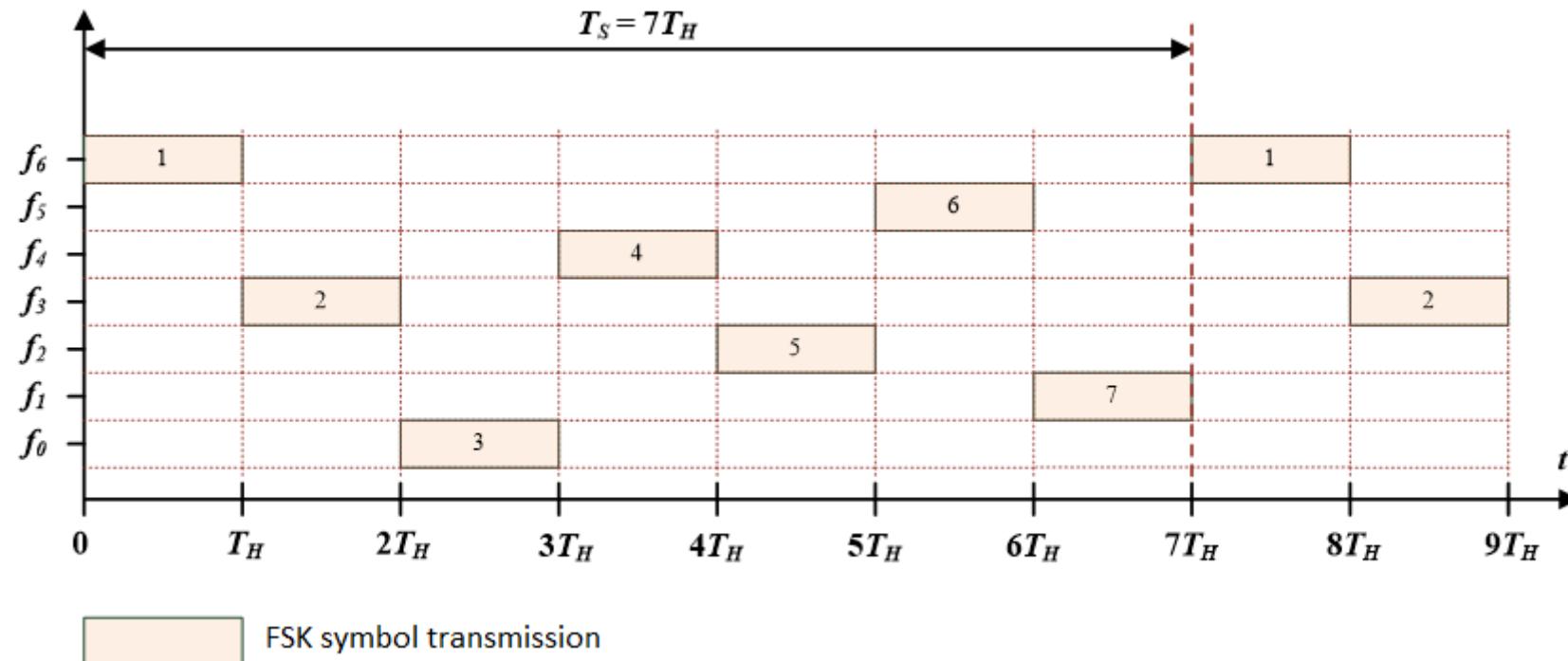


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Fast Frequency Hopping Technique (FFH)



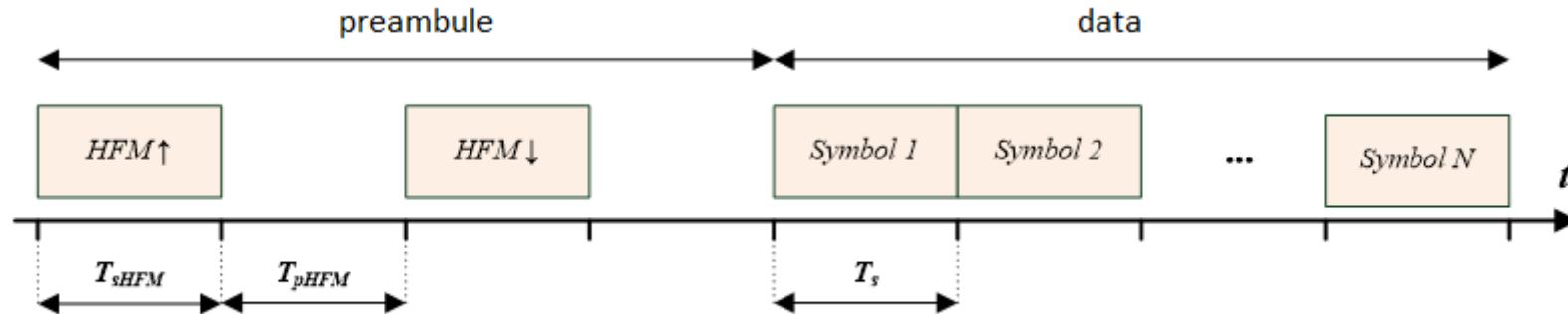
- FFH - spread spectrum technique
- BFSK modulation employed
- All the available channel bandwidth is divided into adjacent narrowband subchannels.
- The carrier frequency is switched between narrowband subchannels by using pseudorandom sequence, which is known to both transmitter and receiver.
- T_H – hop time; the interval time when system receives at a particular carrier frequency between successive hop.
- Clearing time $T_{CC}=7 \cdot T_H$; the time by which each of the narrowband subchannel is unused and the incoming multipath components are extinguish.



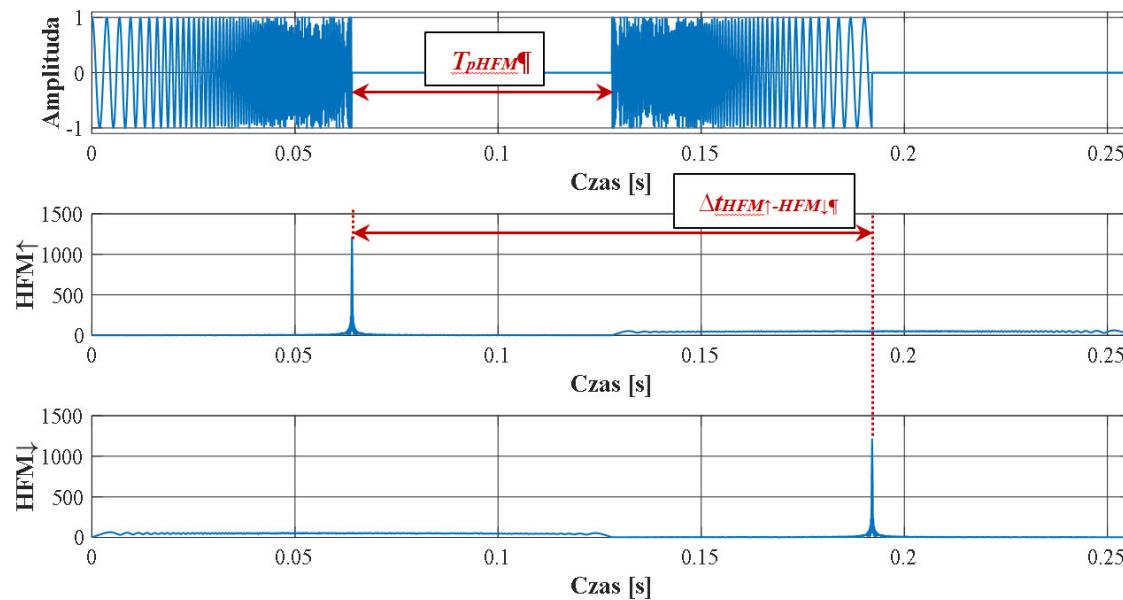


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FFH: synchronization of data frame



Preamble detection



- preamble signal: two pulses – broadband signals with hyperbolically modulated frequency (HFM).
- allows for doppler shift estimation

Doppler shift estimation

$$\tilde{f}_d = \left(\frac{\Delta t_{HFM\uparrow-HFM\downarrow} - T_{pHFM}}{2} \right)^{-1} \text{ [Hz]}$$



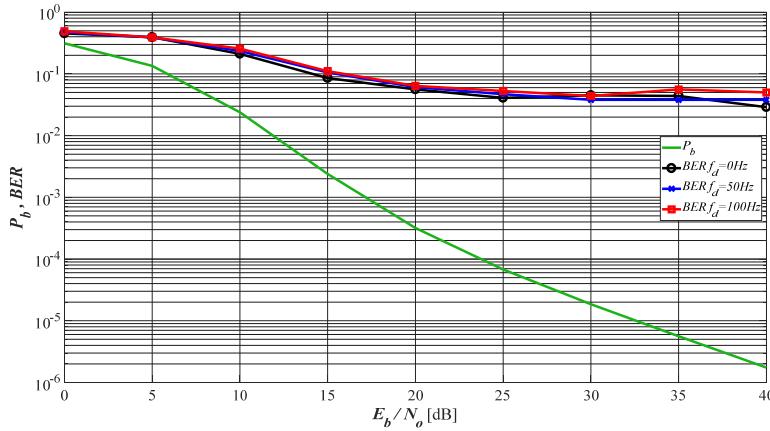
BFSK & FFH-BFSK: simulation tests



Rician fading channel

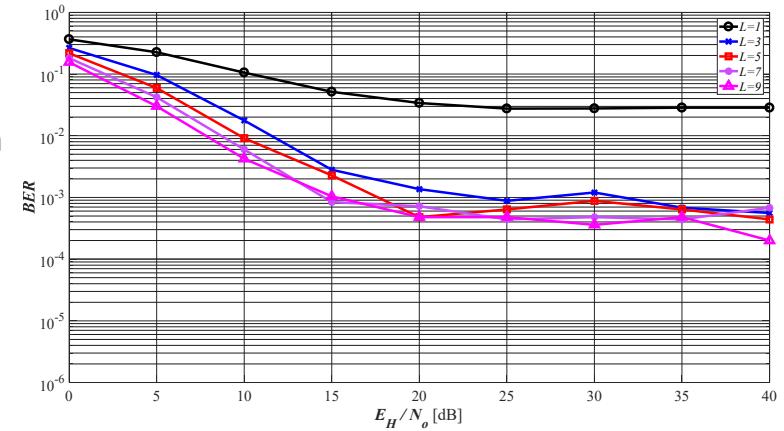
Symbol duration $T_s = 4$ ms, hop time $T_H = 4$ ms

BFSK

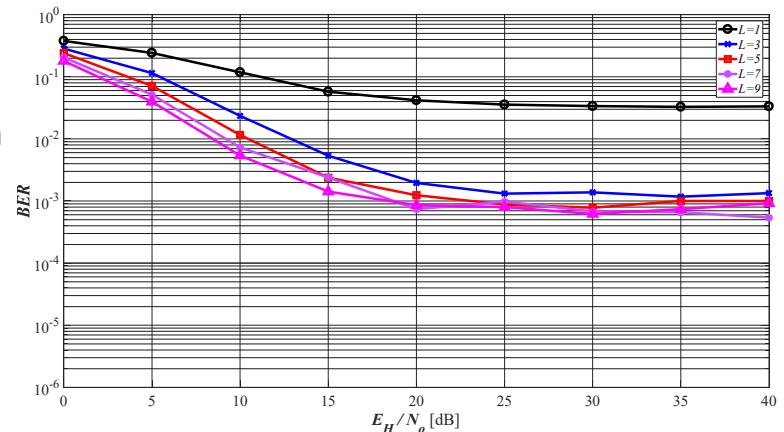
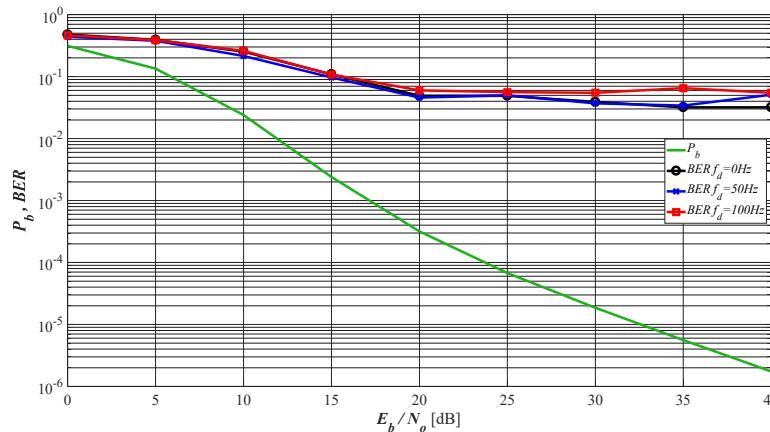


FFH-BFSK

2 propagation paths



3 propagation paths





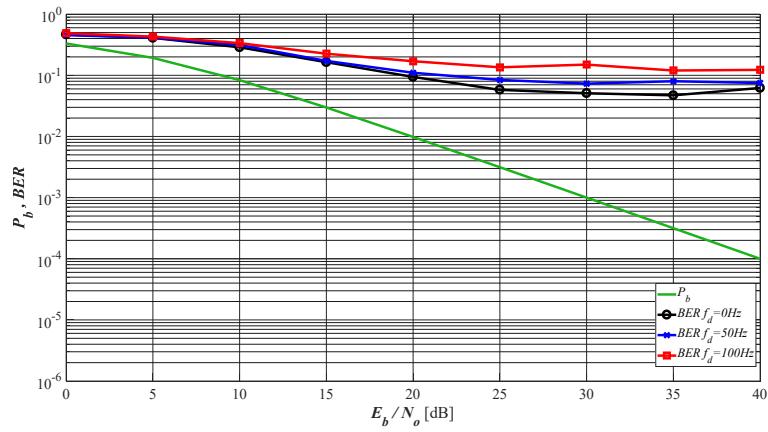
BFSK & FFH-BFSK: simulation tests



Rayleigh fading channel

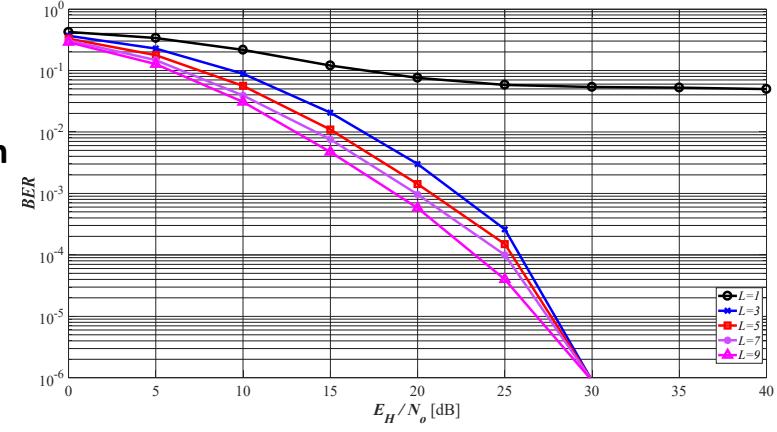
Symbol duration $T_s = 4$ ms, hop time $T_H = 4$ ms

BFSK

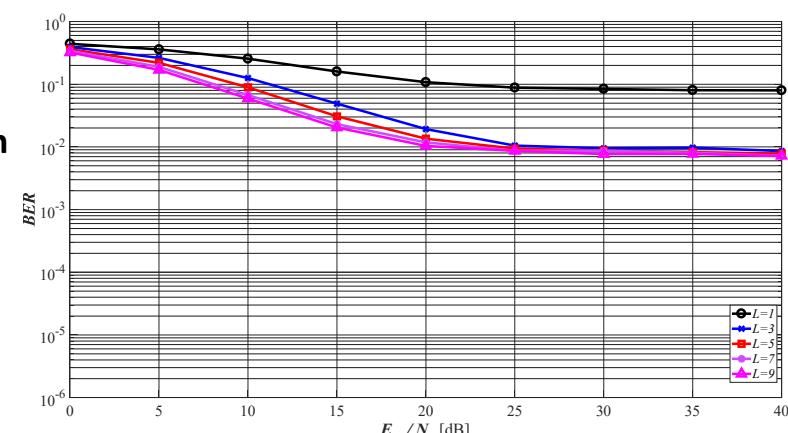
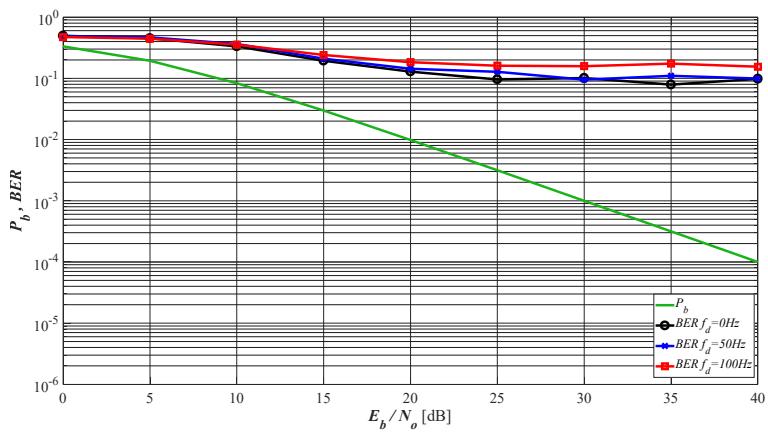


FFH-BFSK

2 propagation paths



3 propagation paths

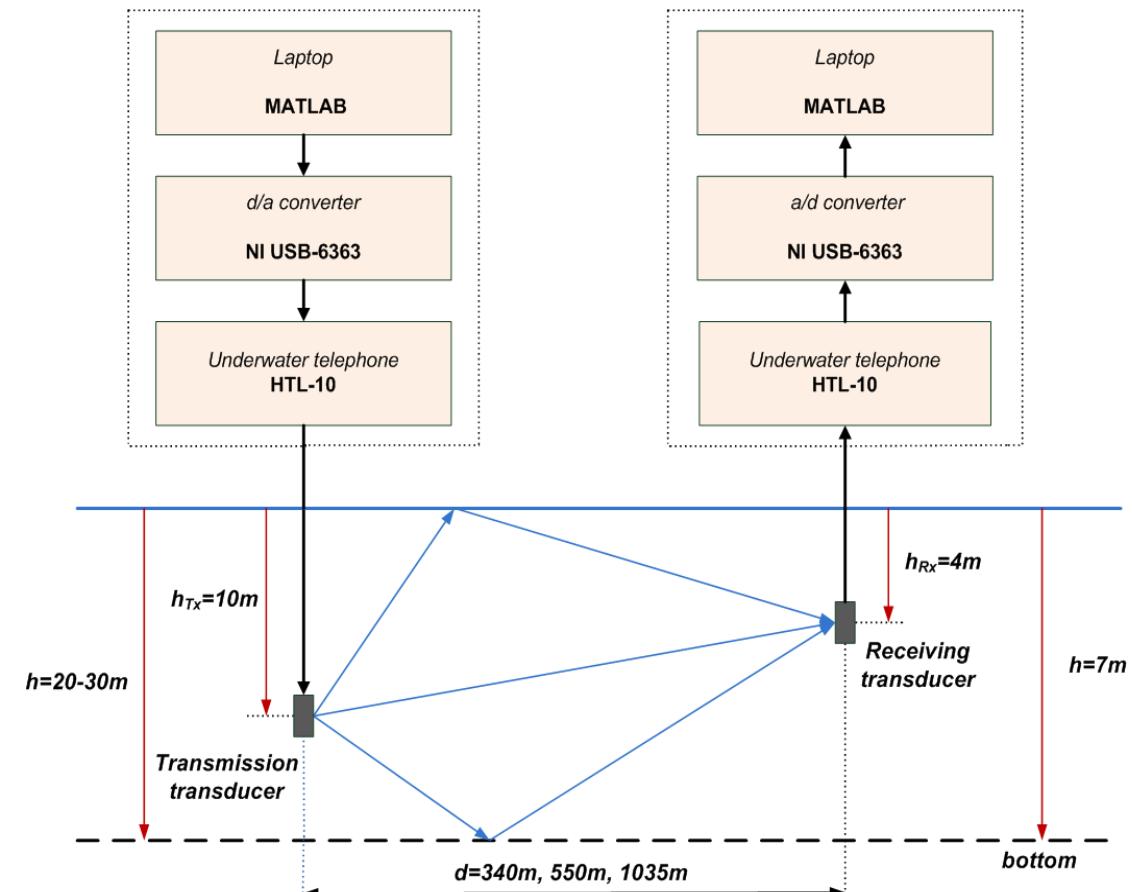
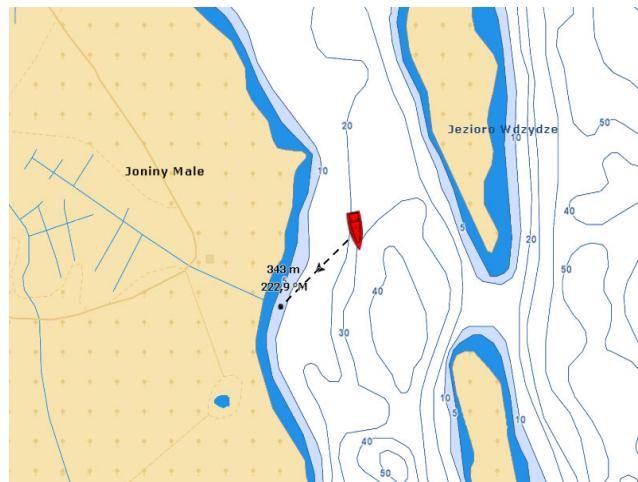




Inland water experiment: Wdzydze Lake, 4-5.05.2017

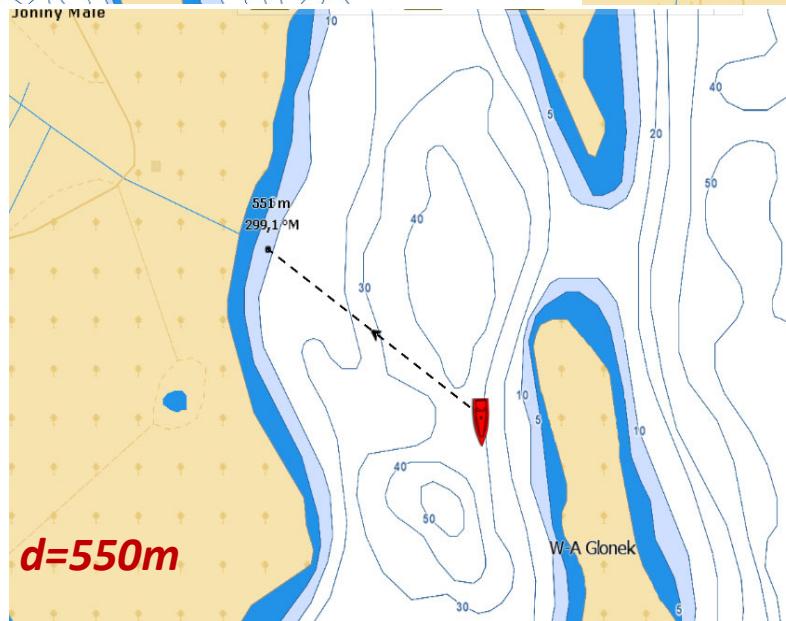
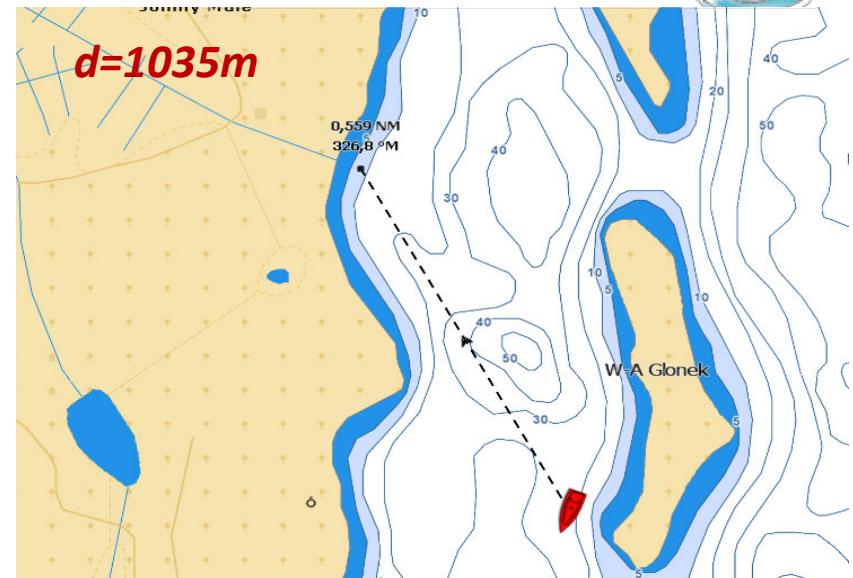
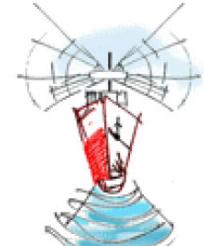


Wdzydze Lake





BFSK & FFH-BFSK: inland water experiment



Vessel – transmitter site

Dot – receiver site



BFSK: inland water experiment



Distance	Symbol duration [ms]	E_b/N_0 [dB]	BER	Data transmission rate [bps]
$d=340\text{m}$	4	31	0.05	250.0
	16	37	0.0027	62.5
	64	43	<0.0012	15.6
$d=550\text{m}$	4	28	0.0405	250.0
	16	34	0.00425	62.5
	64	40	<0.0019	15.6
$d=1035\text{m}$	4	26	0.00673	250.0
	16	32	<0.00094	62.5
	64	38	<0.0012	15.6

Channel delay spread

$T_m = 2 \text{ ms}$

$T_m = 7 \text{ ms}$

$T_m = 9 \text{ ms}$



FFH-BFSK: inland water experiment



Distance	Hop time [ms]	Hop number	E_H/N_0 [dB]	BER	Data transmission rate [bps]
340 m	4	3	31	<0.001	83.3
		5		<0.001	50.0
		7		<0.001	35.7
		9		<0.001	27.8
550 m	4	3	37	0.024	83.3
		5		0.019	50.0
		7		<0.001	35.7
		9		<0.001	27.8
1035 m	4	3	43	0.022	83.3
		5		<0.001	50.0
		7		<0.001	35.7
		9		<0.001	27.8

Channel delay spread

$T_m = 2 \text{ ms}$

$T_m = 7 \text{ ms}$

$T_m = 9 \text{ ms}$



Conclusions



- UAC system performance is strongly related to specific propagation conditions.
- In shallow-water channel - communications is usually possible with $\text{BER} < 10^{-3}$ at data transmission rate lower than 100 bps.
- In the case of FFH-BFSK system this can be achieved even without the use of channel coding or channel equalization technique.
- In the case of OFDM system achieving $\text{BER} < 10^{-3}$ requires the use of channel coding with high redundancy.