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Resolution and Doppler Tolerance of Cognitive System Waveforms

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Introduction

The environment is constantly changing in case of mobile systems and often there is lack of preliminary information about the environment and objects. This complicates the use of adaptation techniques because initial values of system parameters are unclear. In this case additional information must be acquired in real time about the environment. This implies the use of cognitive signal processing [1]. Cognitivity allows the data acquisition system to adapt to particular objects and environment, therefore increasing object detection probability and measurement accuracy (distance to objects and resolution).

A cognitive signal processing algorithm in data acquisition system can be divided into the following tasks: intelligent signal processing; taking into account the information gained about the environment to choose the parameters of a sounding signal to be radiated; continuous acquisition and storage of information about the environment for basic adaptation of the sounding system [1].

Cognitive radar is an actual research topic in radar system engineering. Nevertheless, the cognition concepts could be applied for sonars. To apply the cognitive principle to the data acquisition systems three main stages should be implemented:

- the transmitter should adjust the necessary parameters in an intelligent manner, taking into account size of the target, range and target velocity based on the received information
- the system should include the feedback from the receiver to the transmitter
- intelligent signal processing should be implemented to gather all necessary information for the transmitter adjustment.

Moreover, other relevant information on the environment could be gathered by other sensors working cooperatively with the acquisition system. The cognitive system decision is based on signals gathered on the outside environment on the fly as opposed to knowledge-based (KB) systems [1] where the signal-processing is based on prior information.

According to the location of transmitters and receivers, cognitive monostatic and bistatic sonars can be divided into following categories: monostatic, bistatic/multistatic, hybrid multistatic [2]. Every sonar application has different optimum performance characteristics. For one system, it could be range resolution, for the other Doppler tolerance or even a digital beam steering. Rather than optimizing waveforms for a single design criterion, the intelligent system should be able to synthesize waveforms that provide a smooth tradeoff between competing design criteria [3].

Firstly, this paper discusses possible criterions for some sonar applications and proposes general solution. Secondly, the structure of the flexible MATLAB model will be presented. This model allows us include the intelligent module for the future system development. Finally, modeling of the Doppler effect and estimated resolution of the real system with given sounding waveforms would provide the input for the intelligent signal processing in the prototype.

Sonar applications and possible solutions

Next, we take a closer look at the specific applications and possible feedback solution concerning the digital system, which could change the digital waveform and appropriate reception. The performance should be improved by other adjustments as the frequency and bandwidth of the real system are difficult to change.

The goal of the hydrographic application is to measure the bottom profile with maximum resolution and accuracy within a given range. The environmental effects and feedback values will be:

- in the case of the decreased signal-to-noise ratio (SNR) the output power of the system could be increased by the variable gain control at the transmitter or by the use of phase-manipulated signals [4]. Moreover, this leaves the range resolution value unchanged
- in the case of limited detectability due to the unwanted reflections from fish, other biologic objects, air bubbles, dust and dirt, target reflection registration

could be improved by multiple reflection registration, filtering and tracking or beam steering

- in the case of decreased bottom scattering strength it would be necessary to choose different algorithm for received signal processing; to select different waveform; to use digital beam steering, and to change frequency.

Imaging applications like Sidescan or Forward Looking Sonars (FLS), used for large area efficient sea floor imaging, require higher SNR values at the reception. In this case adaptation could be accomplished as follows:

- increase in SNR by using variable output power or by changing signal length or type
- fading, reverberation and the Doppler effect could be eliminated by proper waveform selection
- sensitivity to the ship motion could be in some extent decreased by beamforming.

In general, the efficient SNR increase and resolution are achievable through appropriate waveform design. However, selected waveforms have different Doppler tolerance at the same range resolution. To study the Doppler tolerance and range resolution of the specific waveforms the MATLAB model was created. Furthermore, this allows us implement additional signal processing algorithms, beamforming and possible feedback values of the cognitive system. The flexible model of the cognition system and later the prototype should include digital signal generation, reception with digital beamforming and optimal filtering. Future development will include the intelligent feedback decision making based on tracking and processing information.

The research showed that previously studied binary phase coded waveforms [4] (Barker and nested Barker codes [5]) are efficient for hydrographic applications, but at the same time Doppler tolerance of those signals is limited. Desirable SNR increase would decrease the Doppler tolerance significantly. Fig. 1 illustrates the maximum target velocities for phase manipulated signals Barker and nested Barker codes. Here, element length corresponds to 4, 8, 16 and 32 carrier signal periods per element and sonar frequency is 250 kHz.

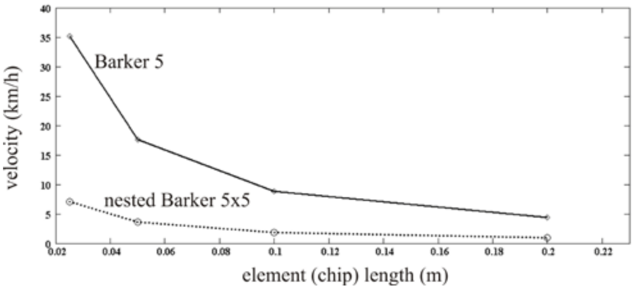

Fig. 1. The maximum target velocities for Barker code signals with 5 and 25 elements

In spite of the fact that phase manipulated codes are more Doppler intolerant, they allow for increasing the system resolution and application distance range could be increased significantly at the same transmitted power level. Thus, for Doppler tolerant cognitive applications further waveform research would be needed [3, 6, 7].

Digital beamforming is the most suitable approach to phased array antenna pattern control. Therefore, it is necessary to model signal reception at the critical target or vessel velocities to determine the properties of the specific waveforms. At the same time we can simulate real system performance in the presence of the Doppler effect.

Wideband beamforming in sonar systems

The beam pattern of the sensor array is typically calculated using harmonic vibrations of infinite duration at a constant magnitude in the case of an electrical scanning, but it is possible to use digital signal processing technology and spread spectrum scanning signals. Derived from the characteristics of this type of signal, the sensor array is not able to use classical phase compensation for the purpose of beam steering. Wideband beamforming algorithm should be used to achieve a high resolution in all partial directions.

The choice of wideband beamforming algorithm in sonar system depends on exact situation, type and length of the probe signal and available hardware. We observed that the general behavioral model is the same and still related to the duration of the shortest element of the signal regarding the dynamics of the scanning signals in the sensor array studied in the previous work [4]. Some differences appeared when using very long nested codes (the average amplitude of the output signal of the sensor array remained somewhat higher for large angles than when using traditional signals), but the choice of scanning signals is not an essential factor with respect to the dynamics. The choice of scanning signal is rather determined by the operating range of sonar and the correlation features of the signal (included the Doppler shift). Comparison of theoretical results suggests that both FDFIB (Frequency-Domain Frequency-Invariant Beamformer) and Block-phase algorithms are realizable and provide very good results. It is also essential that in the case of FDFIB algorithm the amplitude weights only determine the shape of the beam pattern. The level of the side lobes and the beam patterns of any shape can be constructed independent of the frequency. In principle, this method is an alternative to the adaptive methods of forming beam patterns and can be considered the most accurate variant. FDFIB algorithm is based on the properties of the Fourier transform. When switching to a complex envelope, we can find the output signal *M* from sensor *n* at time *l* using the equation

$$\overset{0}{M}_{l,n} = \sum_{p=0}^{KV-1} \sum_{k=0}^{KH-1} A(l - k\tau_e - round\left(fs \cdot n \cdot d \cdot \sin\beta_\gamma / c\right), k + \\ +(p \cdot KH)) \cdot \exp\left(-j\left(\left|\phi_p - \phi_k\right| + \left(\omega_0 \cdot \frac{n \cdot d \cdot \sin\beta_\gamma}{c} \right)\right)\right) \quad , \quad (1)$$

where KH – the number of internal components; KV – the number of external components; A – element function; τ_e – signal initial delay; d – distance between sensors; c – wave speed; ω_0 – support (centre) frequency; fs – sampling frequency; β_γ – partial direction; ϕ_p – phase of *p*-th external component $\phi_p \in \{0°, 180°\}$; ϕ_k – phase of *k*-th internal component $\phi_k \in \{0°, 180°\}$.

For time delay compensation in frequency domain we will use the weight

$$\theta(n,q)=\frac{2\pi q}{(L-1)}\cdot round\left(\frac{n\cdot d\cdot fs\cdot\cos(\beta_{\gamma})}{c}\right),\qquad (2)$$

where q – sampled frequency; L – signal length [4].

By taking the inverse Fourier transform with respect to frequency q, the output electrical signals in each channel are now synchronous. These formulas are modeled in MATLAB environment and sensor output signal and corresponding ambiguity function in case of 5-element Barker code and 5-element sensor array are shown in Fig. 2 and Fig. 3.

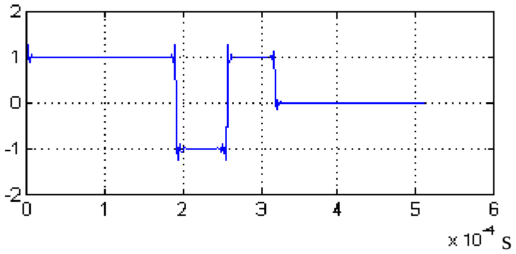

Fig. 2. Sensor output after FDFIB compensation

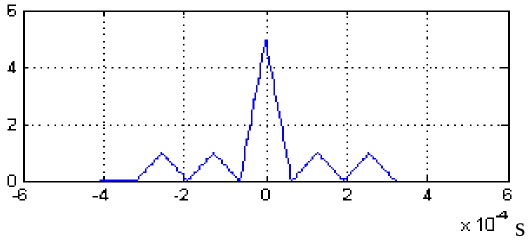

Fig. 3. Vertical cut of the ambiguity function of the optimal filter after FDFIB compensation

As mentioned before, the Barker codes are very intolerant to the Doppler shift. Fig. 4 and Fig. 5 illustrate the matched filter output when objects move towards the sonar system (9 km/h and 20 km/h).

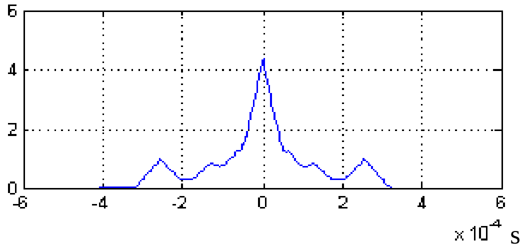

Fig. 4. Receiver output with Barker code waveform affected by the Doppler shift (9 km/h)

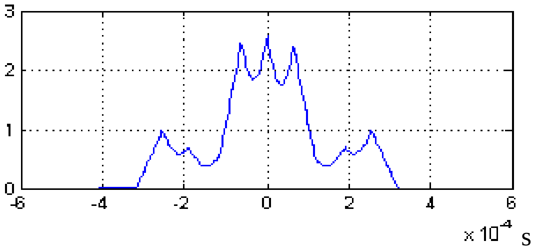

Fig. 5. Vertical cut of the ambiguity function affected by the Doppler shift (20 km/h)

Here vertical cut of the ambiguity function depends only on code and the Doppler shift and modeling results reveal that the Doppler shift can be disregarded when the speed of the object is below 9 km/h. Then vertical cut of the ambiguity function is quite similar to its original. In practice we can obtain sufficient results with speed up to 4.5 km/h as shown in Fig. 6.

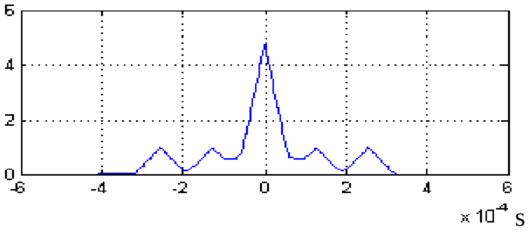

Fig. 6. Receiver output with Barker code waveform affected by the Doppler shift (4.5 km/h)

Obviously, these results are valid for a certain situation. Here we used carrier frequency 250 kHz and 16 signal periods inside one Barker code element. The situation is different when we use longer codes, for example nested code with 5x5 elements. Corresponding ambiguity functions with and without the Doppler shift equal to speed 9 km/h are shown in Fig. 7 and Fig. 8.

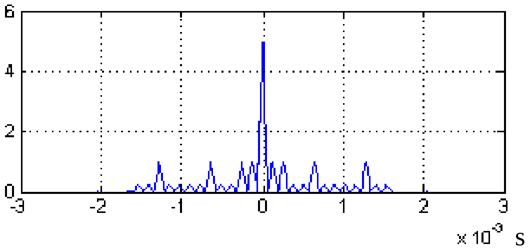

Fig. 7. Optimal filter output of nested Barker without the Doppler shift

As it can be seen from Fig. 8, speed 9 km/h is too high for 5x5 nested codes. Here the Doppler shift can be disregarded if the speed of the object is below 1.7 km/h (Fig. 9).

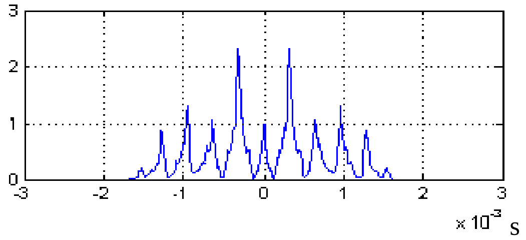

Fig. 8. Optimal filter output of nested Barker affected by the Doppler shift (9 km/h)

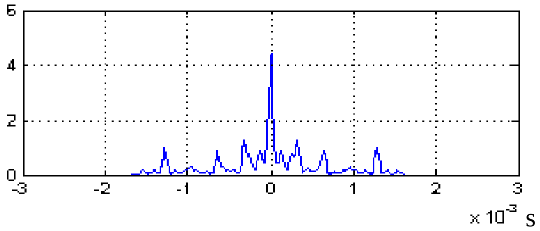

Fig. 9. Receiver output with Barker code waveform affected by the Doppler shift (1.7 km/h)

The question arises: how the Doppler shift will affect the FDFIB beamforming algorithm? It is clear that it has no effect when the signal arrives at the array from the normal direction. In this case the vertical cut of the ambiguity function depends only from code and from the Doppler shift as mentioned before. In the opposite case we can see additional distortions at the output of the matched filter when classical phased array or block-phase algorithm is used. However, FDBIB algorithm is invariant to the scanning signals [4], and the Doppler shift will not affect the FDFIB beamforming algorithm.

Conclusions

The cognitive radar principles could be successfully extended to other data acquisition systems. This paper considers the problems of intelligent sonar system as an illustrative case. It is possible to implement cognitive sonar application with digital signal generation, processing and feedback from the receiver to the transmitter. Intelligence should provide a smooth tradeoff between different criterions. Therefore, one of the main feedback components will be waveform selection, which gives desirable SNR, Doppler tolerance and range resolution. Optimal filtering with digital beamforming facilitates receiver adaptation and also digital beam steering if necessary. The cognitive system basic functions were modeled in MATLAB environment. Discussed model showed that the Doppler tolerance of the system is determined by waveform, and the Doppler shift will not affect the proposed beamforming algorithms. Only low-speed target applications are suitable because the binary phase coded waveforms are relatively sensitive to the Doppler effect. Future research should include waveform design, intelligent signal processing, and feedback modeling and implementing.

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Modern intelligent data acquisition systems use spread-spectrum waveforms and sensor systems with varying parameters according to the state of environment and objects to be tracked. Cognitivity allows the system to adapt to particular objects and environment, therefore increasing object detection probability and measurement accuracy (distance to objects, speed and resolution). This paper discusses the possible future development of a cognitive system with dynamic spread-spectrum waveform design. The active data acquisition system modeling results will provide information about the suitability of proposed waveforms and reception algorithms concerning Doppler tolerance and noisy environment. The devised methods could be implemented in sounding equipment prototypes for further studies. Theoretical and experimental results will be compared and evaluated. Ill. 9, bibl. 7 (in English; abstracts in English, Russian and Lithuanian).

Ю. Бердникова, Т. Рубен, И. Муурсепп, Э. Лоссманн. Резолюция и доплеровская толерантность в когнитивной системе // Электроника и электротехника. – Каунас: Технология, 2010. – № 7(103). – С. 101–104.

Рассматривается использование принципов когнитивности в современных интеллектуальных сонарных системах, что позволяет оптимально согласовывать параметры сигналов и систем датчиков с заданными погрешностями измерения в реальном времени. Результаты моделирования представленных методов, экспериментальная проверка которых будет проведена в дальнейшем, иллюстрируют пригодность к использованию предлагаемых сигналов и алгоритмов приема. Ил. 9, библ. 7 (на английском языке; рефераты на английском, русском и литовском яз.).

J. Berdnikova, T. Ruuben, I. Müürsepp, E. Lossmann. Doplerinis priartėjimas ir rezoliucijos kognityvinėse sistemose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 7(103). – P. 101–104.

Aprašomos intelektualios kognityvinės sistemos, kurios leidžia suderinti jutiklių signalų parametrus ir užtikrina matavimo paklaidas realiu laiku. Pateikiami modeliavimo metodai ir jų eksperimentiniai rezultatai patvirtino, kad pasiūlyti algoritmai tinka intelektualioms sistemoms, kuriose leidžiama naudoti doplerinio priartėjimo teoriją. Il. 9, bibl. 7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).