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Extended summary

De Bruijn Sequences in Spread Spectrum Systems: Problems and Performance in Vehicular Application

Curriculum: Ingegneria Elettronica, Elettrotecnica e delle Telecomunicazioni

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Abstract. This thesis deals with the analysis about a possible utilization of a particular set of sequences, the so-called de Bruijn sequences, in a Direct Sequence Spread Spectrum (DSSS) vehicular radar system. Compared with other spreading codes adopted in DSSS systems, the greater the span of the set, the more the number of de Bruijn sequences exponentially increases and theoretically permits to assign each radar a different generated sequence, as a specific key. By this way it is possible to develop a self-consistent radar system, which is able to work without any infrastructure required to assign sequences, as it happens in the case conventional spreading codes, like Gold or Kasami codes, are adopted. Due to their both favorable auto- and cross-correlation properties de Bruijn sequences are particularly indicated for automotive systems in which there are the needs of detecting accurately a target and performing in a multi-user radar environment. Considering their good correlation properties and their huge number, de Bruijn sequences could be used not only in vehicular radar but also in other Spread Spectrum systems and so, they are evaluated in various scenarios, like downlink and uplink channel of Direct Sequence Code Division Multiple Access (DS-CDMA) systems. In fact, in their standard version, de Bruijn sequences, if accurately selected, have the property of orthogonality, consequently they are tested in a downlink channel of a DS-CDMA system. In addition, from de Bruijn sequences another particular set of sequences, the so-called modified de Bruijn sequences, can be derived. These sequences show better performance in terms of cross-correlation properties and they could be used in uplink channel of DS-CDMA system. In order to verify the performance in a real test-bed, a preliminary implementation on Software Defined Radios (SDR) is also developed. Finally these sequences are adopted and compared in simulated multi-user DSSS radar scenarios. The analysis done and the performance results obtained suggest to evolve this radar solution to a cognitive radar approach, using computer vision systems as external aid sensor, which can outperform actual solutions.

Keywords. Code Division Multiple Access, De Bruijn sequences, Direct Sequence Spread Spectrum Radar, Software Defined Radio, Vehicular Radar.

1 Problem statement and objectives

The development of effective anti-collision warning radars is a key step in the technological initiatives promoted to improve road safety, and efficiency of transport systems. Many proposals have been discussed and evaluated up to now, focusing on advanced pilot/driver assistance systems, in support of vision, alertness, maneuvering, and automated driving compliance with the regulations [1][2][3][4][5][6]. The ultimate objective remains crash prevention, through an accurate knowledge of the location, speed, acceleration or deceleration of the nearby vehicles. Automotive radars provide an automatic vision of the environment where the vehicle is moving, to draw the information required for guaranteeing, as much as possible, safety for the vehicle and the passengers on-board. At the same time, road safety is also increased by implementing a communication system, able to exchange information among vehicles, that, by this way, get an active role; each vehicle transmits its navigation data, like position, speed, brake status and so on. An important goal consists in integrating the two safety systems, radar and communication, in order to simplify (and reduce the cost of) the on board installation. The research on radar technology for automotive applications started in Germany in 1973, and the first prototype was a non-coherent pulsed radar working at 35 GHz. The research was put aside for about a decade. The activity started again at the end of 80's, thanks to the advances in millimeter waves and the interest expressed by all the most important automotive companies. In the subsequent years, radar sensors were integrated in collision avoidance and Autonomous Intelligent Cruise Control (AICC) systems. The latter, in particular, exploit the information provided by the radar to adapt the car speed to that of the preceding vehicle, in such a way as to maintain a constant distance between them. Two kinds of radar are introduced for automotive applications: Short Range Radars (SRRs), and Long Range Radars (LRRs) [28][37][59][70][71][72]. The SRR permits a precise speed measurement combined with accurate radial range information. To obtain the required resolution (approximately 5 to 10 cm), the SRR needs a large bandwidth of 4 GHz for the range measurement. LRRs operate between 76 GHz and 77 GHz with a maximum bandwidth of 1 GHz. They allow an operating range up to 150 m, and are used at vehicle velocities not below 30 km/h. One or multiple narrow lobes control and scan the driving path in front of the car, to determine the distance to the vehicle ahead, and maintain a constant, minimum safety gap. Classic Frequency Modulation-Continuous Wave (FM-CW) systems are very simple to implement, but can be strongly degraded because of the interfering signals produced by neighboring radars of the same type. Classic LRR implementations employ signal-processing techniques based on Frequency Modulation-Continuous Wave (FM-CW) transmission, and a bandwidth of 1 GHz at the most. FM-CW systems are very simple to implement but their performance can be strongly degraded because of the interfering signals produced by neighboring radars of the same type. Radars employing Spread Spectrum (SS) Pseudo Noise (PN) methods in Direct Sequence (DS) configuration overcome this limitation. The specific PN sequence acts as the radar: the distance of a vehicle is determined by selecting its echo in a very large set of interfering signals, echoes, and other radars. The auto-correlation properties of the single signature determine the accuracy in distance evaluation; the cross-correlation properties of the whole set of signatures shared among the vehicles provide rejection capability with respect to interfering radars. Another important aspect concerns the number of signatures available that usually depends on the sequence length. The bandwidth constraint does not allow to arbitrarily extending the sequence length, to increase the cardinality of the signature set. Consequently, a common limitation to face is the relatively small set of PN signatures available, of a given length, and able to satisfy precise requirements on auto- and cross-correlation properties. Different families of binary sequences have been studied for automotive DS-SS radar applications. Besides the classical maximal length sequences (the m-sequences) and Gold sequences, chaotic signals featuring very favorable auto- and cross-correlation properties have been considered [7][17][18][19][20][30]. Moving from these basic considerations, the thesis explores the applicability of de Bruijn sequences in DS-SS radars, as an alternative to classical solutions. De Bruijn sequences have been studied for many years [8][11][21][33][61][69]. Their construction has been extensively investigated, and several different generation techniques proposed in the literature [9][10][14][24][62][63]. One of their most valued properties is the huge cardinality; on the other hand, not so much is known about their correlation features [12][13][68]. If adequate, it would be possible to adopt de Bruijn sequences to implement either the DS-SS radar system and the communication system, thanks to the huge number of different users that may share the radio channel through a Code Division Multiple Access (CDMA) scheme. Radar performances are usually evaluated in terms of a high detection capability joint a low false detection rate; the analysis in this paper will be mainly focused on such performance figures. After an accurate analysis of the correlation properties of de Bruijn sequences and modified de Bruijn sequences, compared with other PN codes, these sequences are used in four different scenarios.

2 Research planning and activities

At first the research activities focused on the implementation of various modem on Software Defined Radio, due to the natural prosecution of the argument chosen for the MS Degree and on Computer Vision applications due to the collaboration with Aethra Video srl for the Regione Marche project called TASCA. During the first year, research activities have been extended to Direct Sequence Spread Spectrum Radar system and, in particular, to the analysis of de Bruijn sequences as spreading codes. An accurate research on the state of the art of these arguments was done during the first year and, sometime, during the second year. Subsequently, the novel ideas have been investigated from theoretical point of view and through applications in different scenarios.

Various tools and technologies have been adopted. The Small Form Factor Software Defined Radio Development Factor, which is a hybrid FPGA/DSP board, has been used to develop a test-bed for a DSSS radar system. The main tools related to this board are MATLAB/Simulink from Mathworks, Xilinx ISE and Xilinx System Generator for DSP. Visual Studio and Xcode have been used to develop several algorithms both for Windows and Macintosh and, in particular, the algorithm that generates the de Bruijn sequences. Analytical evaluations have been also performed using Mathcad tool. To validate the test-bed, some Rhode&Swartz Devices, like Spectrum Analyzer and Function Generator have been used in conjunction with the WinIQSim Tool provided.

Novel contributions were presented in several international conferences in order to compare results with other research teams and discuss the potentiality of the research field.

3 Analysis and discussion of the main results

De Bruijn sequences over the binary alphabet are those sequences in which every binary n-tuple occurs exactly once over a period. They may be generated by n-stage nonlinear feedback shift registers, as they shall include also the zero state, which cannot be included if a linear shift register is adopted for the generation process. When binary de Bruijn sequences are considered, for a given value of n there are a total of $2^{2^{(n-1)}-n}$ sequences in the set, each of period 2^n. De Bruijn sequences have many desirable properties, such as long period and low predictability, and can be used as stream ciphers in cryptographic applications. As discussed by Mayhew in [12], a de Bruijn sequence may be also obtained by adding a single zero to the longest run of zeros in an M-sequence (maximum length sequence), thus obtaining a so called *primitive* de Bruijn sequence; at the same time, a *modified* de Bruijn sequence is obtained when removing a zero from the all zero n-tuple of a de Bruijn one.

3.1 Comparison between de Bruijn sequences and other sequences

De Bruijn sequences are maximal period binary sequences, so their length is always an even number. When comparing the total number of de Bruijn sequences of length N to the total number of available maximal length sequences (m-sequences) or Gold sequences or Kasami sequences, similar but not identical length values shall be considered, as reported in Table 1, values for the de Bruijn sequences are obtained from the formula given before.

Table 1: Length and total number of m-sequences, Gold, Kasami and de Bruijn sequences for the same span n (3≤ n ≤ 10).

	m-sequences		Gold		Kasami		De Bruijn	
n	length	N° seq	length	N° seq	length	N° seq	length	N° seq
3	7	2	7	9	//	//	8	2
4	15	2	15	17	15	64	16	16
5	31	6	31	33	//	//	32	2048
6	63	6	63	65	63	520	64	2^{26}
7	127	18	127	129	//	//	128	2^{57}
8	255	16	255	257	255	4096	256	2^{120}
9	511	48	511	513	//	//	512	2^{247}
10	1023	60	1023	1025	1023	32800	1024	2^{502}

As it is shown, the huge cardinality of the set permits to use these sequences both as a key and as spreading sequences in DSSS radar system. In order to validate this statement, both auto- and cross-correlation function side-lobe values have to be compared with the most common set of sequences used. A preliminary analysis has been done comparing span-5 sets of m-sequences, Gold sequences, chaos-based sequences and de Bruijn sequences. Results obtained suggest to carry on the analysis because they show good auto-correlation side-lobe values and, if a subset is properly selected, also good cross-correlation values [42][43][49].

3.2 De Bruijn sequences generation algorithm

The generation a set of sequences is a well-known field of application related, to spreading codes [8][15][16][23][35][38][39][41][62]. Usually the use of a shift register is the preferred solution in particular when it is important to run-time generate a particular sequence. However, if the is a need to generate a set of sequences instead of a single sequence, in order to test the cross-correlation function between them, a shift register approach could result not suitable, especially if the cardinality of the set to be generated is very huge. This is precisely the case of de Bruijn sequences generation, the full set of which, depending on the span chosen, has a cardinality that increases exponentially. A useful overview of possible alternative approaches suggested in the literature may be found in [9][10][14][24][62][63], but they are cases where the generation is performed for a single sequence or for the completely set of sequences without any constraint. In this thesis an algorithm able to generate a subset of de Bruijn sequences with good cross-correlation values is developed. Basically it consists in a binary tree generation in which, when two generation paths share a common pattern of bits in their initial root, one of them is pruned in order to reduce a priori the number of sequences that will provide high cross-correlation due to the presence of common bit patterns. Using this algorithm various subsets of sequences with high span have been generated and tested.

3.3 De Bruijn sequences in four different scenarios

Four different scenarios have been considered in order to test de Bruijn sequences performance:

- DS-CDMA system: this system could be a possible technology used in an Inter-Vehicle-to-Vehicle (V2V) communication system;
- Deep-Space communication scenario, Mars Exploration Rover (MER) Entry, Descend and Landing (EDL): Doppler resolution of de Bruijn sequences permits a possible utilization in this field of application;
- Real-Implementation on Software Defined Radio (SDR): in order to validate a possible real-time hardware implementation of the automotive radar system;
- Simulation model of a non-stationary real-like multi-user DSSS radar system: the huge cardinality of the de Bruijn sequences with their good both auto- and cross-correlation properties suggest to use them as a key and as a spreading sequence in a multi-user automotive scenario.

In DS-CDMA scenario, both de Bruijn and modified de Bruijn sequences have been tested in uplink and downlink channel using the method of the characteristic function. Due to the favorable cross-correlation values of modified de Bruijn sequences they have been proposed as a possible solution for the uplink channel of a DS-CDMA system [34][46]. Due to the orthogonality property of de Bruijn sequences, they have been proposed as a possible solution for the downlink channel of a DS-CDMA system.

In MER-EDL [44][45], an analysis of the Doppler resolution features through Ambiguity Function (AF) [25] has been performed using the Doppler value known for all the stages. As shown in Figure 1, values obtained are compared with other spreading sequences. Results shows that de Bruijn outperform Gold codes for the selected Doppler resolution [51].

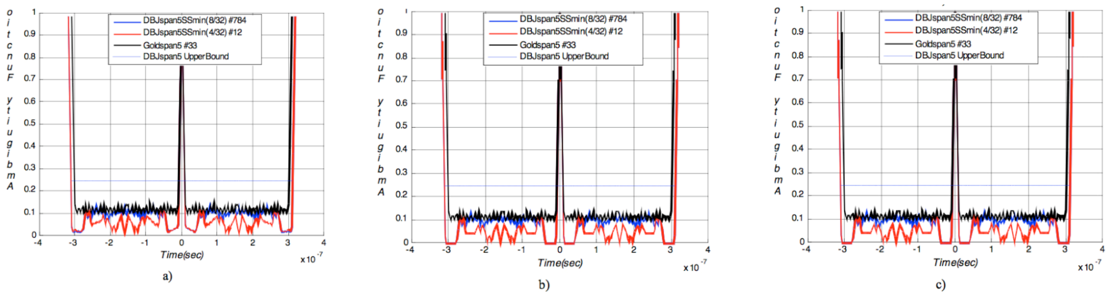

Figure 1: Average normalized PAF Doppler cuts at a) 392.16 kHz, b) 23.22 kHz, and c) 1.3 kHz, for de Bruijn and Gold sequences, n = 5, 2PSK modulation and no pulse shaping.

The test-bed implementation on SDR has been performed using a span-7 sequence with 10 nsec of Chip time. The channel has been simulated using coaxial cables, power splitters and attenuators. The results of the implementation have been verified by simulation and through a laboratory setup, providing satisfactory performance [50]. The range resolution may be increased with continuous wave processing and resorting to other hardware solutions.

Regarding to the simulation model, several situations have been considered. One of these, shown in Figure 2, has been particularly tested using de Bruijn, modified de Bruijn, Gold and m-sequences, and several Constant False Alarm Rate (CFAR) decision algorithms.

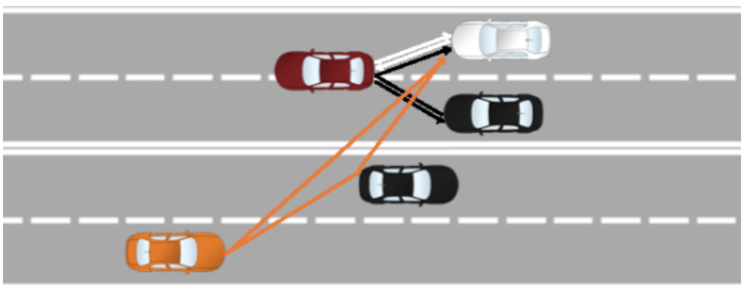

Figure 2: One of the multi-user automotive scenarios considered

Results obtained have been shown that de Bruijn sequences, due to the particular autocorrelation property to have null values near the correlation peak, outperform the other sets tested in particular considering False Alarm Rate as it is shown in Table 2.

Table 2: Correct Detection and False Alarm rate obtained using the scenario in Figure 2

	Log-CFAR		Abs-CFAR		X^2-CFAR		IV-CFAR	
	C.D.	F.A.	C.D.	F.A.	C.D.	F.A.	C.D.	F.A.
m-	0.9999	0.0068	0.9999	0.0051	0.6600	0.0078	0.7625	0.0036
Gold	0.9999	0.0055	0.9999	0.0047	0.6622	0.0068	0.7547	0.0036
de Bruijn	0.9989	0.0040	0.9977	0.0038	0.2792	0.0055	0.7605	0.0036
m. de Bruijn	0.9911	0.0053	0.9933	0.0043	0.2687	0.0058	0.7748	0.0038

Conclusions

This dissertation focused on the possible adoption of the so-called de Bruijn sequences, in both standard and modified version, in a DSSS multi-user automotive radar system. The analysis done on the correlation properties, compared with conventional spreading codes, shows favorable side-lobe values with a very huge cardinality of the set. This suggests the adoption of de Bruijn sequences both as spreading codes and as personal unique keys in a DSSS multi-user automotive radar system. The problem of their generation is also engaged and an algorithm, which is able to generate a subset with good cross-correlation properties, is developed. De Bruijn sequences are then tested in four different applications: in a DS-CDMA system, in a Entry, Descend and Landing stages of Mars Exploration Rover, in a Software Defined Radio Development Platform and in a non-stationary DSSS multi-user automotive radar system. Results obtained show that, due to their particular correlation properties, they outperform applications with other more conventional set of sequences and confirm the possible adoption of these sequences in a real system. Future works could be oriented towards the extension of this radar system to a cognitive radar system using vision-based technologies[75][65][74].

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