Adaptive PN code acquisition in multi-path spread spectrum communications using FPGA

B.Wei, MY. Sharif, TD. Binnie, AEA. Almaini
School of Engineering & The Built Environment, Napier University, Edinburgh, United Kingdom
E-mail: B.Wei@napier.ac.uk

***Abstract*—In multi-path spread spectrum communications, signals from different paths may affect the performance of the Pseudo-Noise (PN) code detectors. In this paper, the performances of two PN code detectors, Cell Averaging Constant False Alarm Rate (CA-CFAR) and Order Statistics CFAR (OS-CFAR) are analysed and compared in terms of the Mean Acquisition Time (MAT) and Probability of Detection (P_D). The detectors utilise a digital Matched Filter (MF). Complexity and hardware consumption with Field Programmable Gate Array (FPGA) implementation are taken into comparison to determine the CFAR detector with the best performance.**

I. Introduction

Code acquisition is one of the two processes in code synchronisation, which coarsely aligns the received PN code and the locally generated code. Following the code acquisition, the process of tracking is used by the spread spectrum receiver to further align the two sets of codes.

In multi-path communications, signals are transmitted from different channels, and the signals arrive at the receiver with different time delays. The RAKE receiver can be used to combine the power of the signals from different channels if their delays are known [1]. CFAR is an adaptive technique which can be used to detect time delays required in RAKE receiver. This adaptive technique improves the performance of PN code acquisition in comparison with the fixed threshold techniques, especially in communications with time varying noise in the channel. In multi-path communications, the performance of CA-CFAR is affected by the multi targets interferences [2]. However, the performance of OS-CFAR may not be seriously affected by the multi targets interferences as only one cell is used in the threshold calculation. By selecting an adequate order for the OS-CFAR detector, the interferences caused by multi targets can be reduced. Simulation results are presented in section IV which confirm the superior performance of the OS-CFAR detector. Considering FPGA implementation, the adequate order for the OS-CFAR detector is also simplest to achieve using the Bubble Sorting technique [3].

II. Matched filter acquisition with CFAR detectors

There are two main types of CFAR techniques which are widely used. These are known as CA-CFAR and OS-CFAR [4]. Figure 1 shows the block diagram of CA-CFAR and OS-CFAR detectors. The difference between the two detectors is in the method of obtaining the adaptive threshold, which can be calculated by multiplying a fixed scaling factor T and an adaptive value Z. For CA-CFAR, Z_{CA} is the average value of N cells on the two sides of the cell tested, and for OS-CFAR, Z_{OS} is the K_{th} biggest sample of N cells.

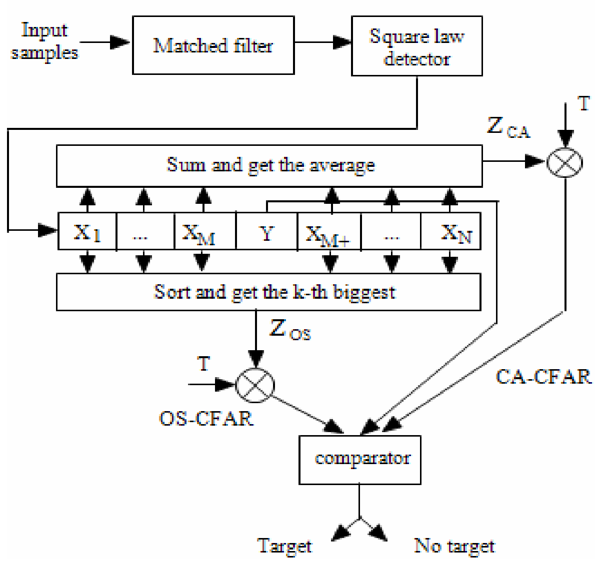

Figure 1. Block diagram of CA-CFAR and OS-CFAR detectors

Assuming that the received noise is Gaussian distributed, the signals in reference cells are Raleigh distributed, the different cells are independent and identically distributed then for a single-path communication, the probability of false alarm (P_{FA}) for CA-CFAR and OS-CFAR can be calculated by the following equations [4]:

$$P_{FA}(CA) = \frac{1}{(1 + T/N)^N} \tag{1}$$

$$P_{FA}(OS) = k\binom{N}{K}\frac{\Gamma(N-K+T+1)\Gamma(K)}{\Gamma(N+T+1)} \tag{2}$$

In (1), N is the number of reference cells, and T is the scaling factor for threshold calculation. When P_{FA} has been chosen, T is the only unknown parameter in the equation for a fixed N, so it can be easily calculated by (3):

$$T = N(P_{FA}^{-1/N} - 1) \tag{3}$$

In (2), there is one more parameter K, which denotes the order of the OS-CFAR detector. Γ is the gamma function and can be expressed as:

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \qquad (4)$$

After obtaining the scaling factor T, the P_D for CA-CFAR and OS-CFAR detectors can be calculated by (5) and (6), where λ is the Signal-to-Noise Ratio (SNR) [4]:

$$P_D(CA) = \frac{1}{\{1+(1+\lambda)T/N\}^N} \qquad (5)$$

$$P_D(OS) = k\binom{N}{K}\frac{\Gamma[N-K+T/(1+\lambda)+1]\Gamma(K)}{\Gamma[N+T/(1+\lambda)+1]} \qquad (6)$$

III. MULTI-PATH SPREAD SPECTRUM COMMUNICATIONS

In single-path communications, the MF produces a correlation peak at every period of the PN code, but in multi-path channels, due to different delays for different channels, the MF will find more peaks in one period of the PN code. Figure 2 shows the output of the MF for a single-path communication and a 2-path communication. The outputs have the relation as shown in (7) [5]:

$$A^2 = B^2 + C^2 \qquad (7)$$

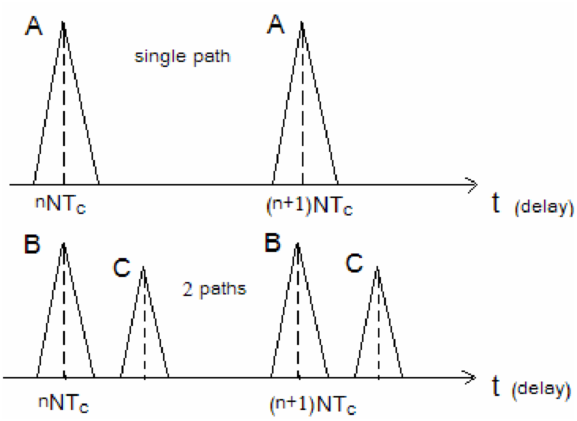

Figure 2. Matched filter output for single-path and 2-path communications

In CFAR detectors, the output from the MF is sampled and applied to the reference window for threshold calculation. Correlation peaks from different channels may exist in the reference window at the same time, and this will affect the calculation of the correct threshold. Therefore, for multi-path communications, the CFAR equations need some modification compared with single-path communications as follows.

For CA-CFAR detectors, when the interfering targets exist, the P_D can be obtained from (8):

$$P_D(CA) = \frac{1}{\{1+(1+\lambda_1)T/N\}^{N-J}(\frac{T\lambda_1}{N\lambda_2}+1)^J} \qquad (8)$$

Where, λ_1 is the SNR for the desired signal, λ_2 is the average SNR for the interfering targets and J is the number of interfering targets. In this paper, the signals from different channels are assumed to have the same power. Therefore, (8) can be modified to (9):

$$P_D(CA) = \frac{1}{\{1+(1+\lambda)T/N\}^{N-J}(\frac{T}{N}+1)^J} \qquad (9)$$

For OS-CFAR detectors, (6) must be modified in the case of multi-path communications. If the K_{th} biggest sample is not the interfering targets, P_D for OS-CFAR can be calculated by (10):

$$P_D(OS) = k\binom{N}{K}\frac{\Gamma[N-K+T/(1+\lambda-10\log(J+1))+1]\Gamma(K)}{\Gamma[N+T/(1+\lambda-10\log(J+1))+1]} \qquad (10)$$

Beside P_D, MAT is another factor that can be used to analyse the performance of PN code detectors effectively. It represents the average time to coarsely match the received and locally generated PN codes within the chip time (T_C). In this paper, the performances of CA-CFAR and OS-CFAR are also analysed with MAT. Taking a 2-path communication as an example MAT can be calculated as follows [5]:

$$\begin{aligned} MAT = & \frac{P_{M1}P_{M2}[2T_C+(N-2)(T_C+T_{FA}P_{FA})]}{1-P_{M1}P_{M2}} \\ & + \frac{(N-2)(N-1)(T_C+T_{FA}P_{FA})}{2N} \\ & + \frac{(N-1)(P_{D1}+2P_{D2}P_{M1})T_C}{N(P_{D1}+P_{M1}P_{D2})} \\ & + NT_C\frac{P_{D1}P_{M2}[2T_C+(N-2)(T_C+T_{FA}P_{FA})]+P_{D2}T_C}{N(P_{D1}+P_{M1}P_{D2})} \end{aligned} \qquad (11)$$

Where, P_M is the probability of missing a correlation peak, $P_M = 1- P_D$, T_{FA} is the penalty time for a false detection and NT_C denotes bit interval T_b.

IV. PERFORMANCE ANALYSIS

Firstly, P_D for CA-CFAR and OS-CFAR detectors is analysed for different numbers of paths, with 16 reference cells, K equal to 10 and P_{FA} equals to 0.0001. The results are shown in figures 3 and 4.

From the simulation results, it is easy to see that when the path number is increased, the P_D of CA-CFAR is decreased significantly. Compared with the CA-CFAR detector, OS-CFAR is much better in P_D for the same number of paths. Taking a 2-path communication as an example, the MAT of CA-CFAR and OS-CFAR detectors are compared and the result is shown in figure 5. T_{FA} is set to $10T_b$ and $T_b = 256T_C$.

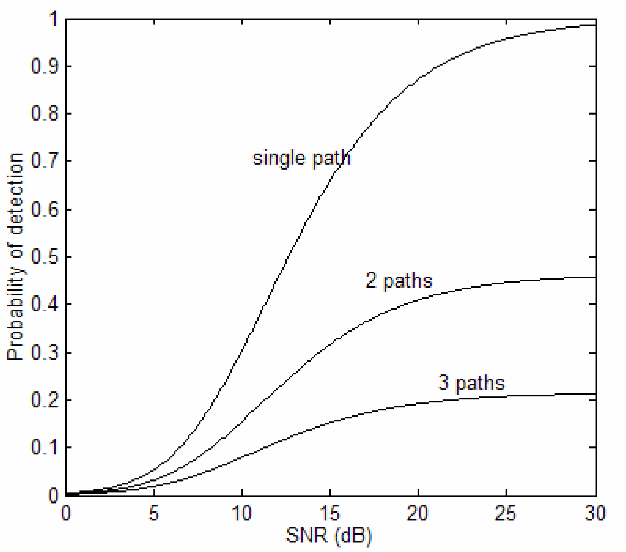

Figure 3. Probability of detection for CA-CFAR detectors

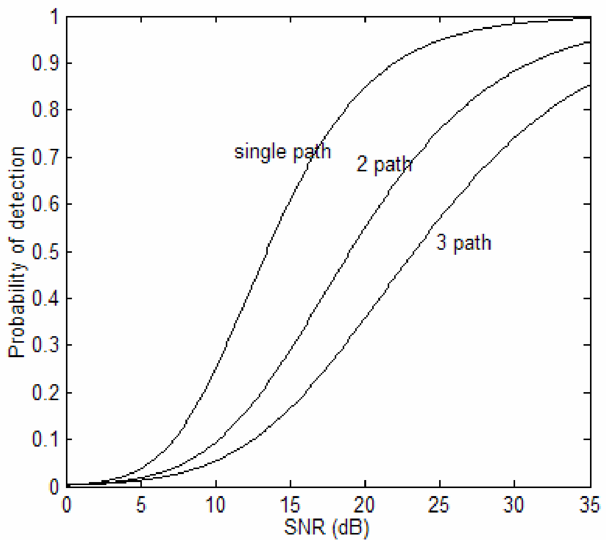

Figure 4. Probability of detection for OS-CFAR detectors

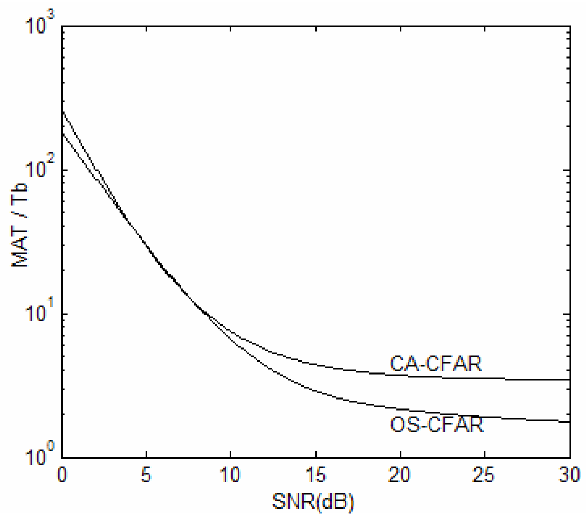

Figure 5. Mean acquisition time for CA-CFAR and OS-CFAR detectors in a 2-path communication

Figure 5, illustrates the performance of CA-CFAR and OS-CFAR detectors in a 2-path communication. Only when the SNR is less than 5 dB, a CA-CFAR has little advantage over an OS-CFAR. For the SNR greater than 5dB, the performance of OS-CFAR is better than CA-CFAR. The higher the SNR, the shorter the MAT for both detectors. However, the reduction in MAT of OS-CFAR is more significant. Also, from figures 3 and 4, it can be seen that when the number of paths is increased, the performance of a CA-CFAR detector deteriorates faster than an OS-CFAR detector.

In this paper, a 2-path communication is chosen for performance analysis and 16 reference cells are used in the CFAR detectors. To avoid the interfering target in the reference window, the order of OS-CFAR must be less than 14; hence the OS-CFAR detectors with K equal 14, 12, and 10 are simulated and compared.

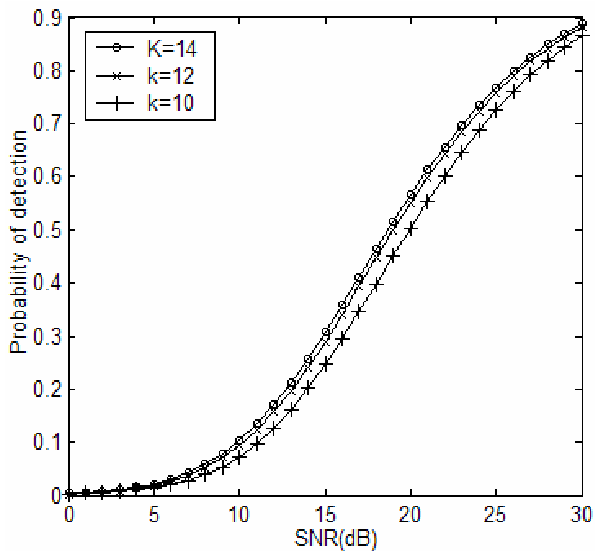

Figure 6. Probability of detection for OS-CFAR detectors with different K (N=16)

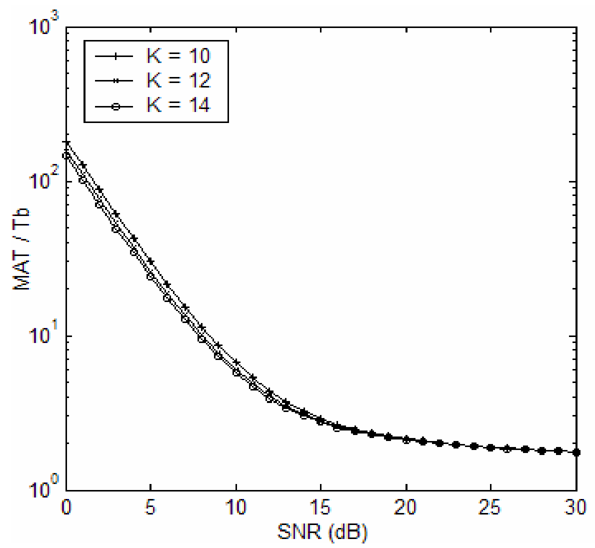

Figure 7. Mean acquisition time for OS-CFAR detectors with different K (N=16)

Figures 6 and 7 show the P_D and MAT for OS-CFAR detectors with different K. Obviously, the OS-CFAR detector with K equal 14 has the best performance in terms of highest P_D and the shortest MAT. The performance deteriorates when K is decreased. Thus, in a M-path communication, if N reference cells are used, the OS-CFAR detector with K equal (N-M) has the best performance.

V. REALISATION OF MATCHED FILTER WITH OS-CFAR DETECTORS USING FPGA

A. *Structure of Matched Filter with an OS-CFAR detector*

A 256-coefficient MF with an OS-CFAR detector is presented in this paper. The MF part of the circuit is designed with the pipeline structure. Figure 8 shows the structure of the MF with transposed Finite Impulse Response (FIR) structure. The merit of using a transposed FIR structure is the lower input to output latency [6]. An 8-bit input is used for the MF and as the MF length is 256, the width of pipelines used in the MF and the reference window need to be $8 + \log_2^{256} = 16$ bits.

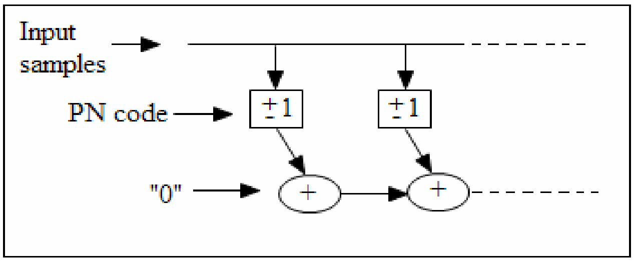

Figure 8. Matched filter with transposed FIR structure

Bubble Sorting is used to find the K_{th} biggest sample in the reference cells. Figure 9 illustrates the process of Bubble Sorting. The samples in the reference cells are labelled from X_1 to X_N. To find the biggest sample, N-1 comparisons are needed as shown in the figure.

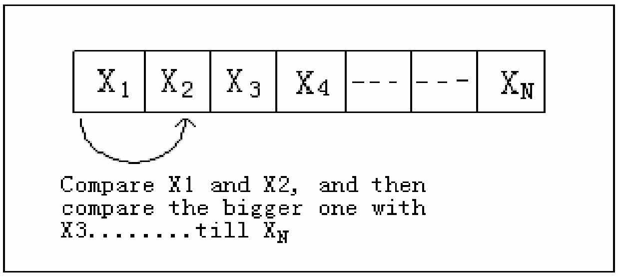

Figure 9. Bubble sorting used in OS-CFAR detectors

When the biggest sample is found, to identify the next biggest one, the number of comparisons needed is N-2. Therefore, to find the K_{th} biggest sample in N samples, the number of comparisons required can be calculated by (12):

$$N_{Com} = \sum_{a=K-1}^{N-1} a \qquad (12)$$

Thus, for OS-CFAR detectors that have been simulated in this paper, using (12), it is easy to determine that the detector with K equal to 14 is the simplest to achieve as only 42 comparisons are required to find the 14_{th} biggest sample in the reference window. Also, from figures 6 and 7, the OS-CFAR detector with K equal to 14 is the one with the best performance, therefore, the most suitable for implementation with FPGA.

B. *Simulatons and layout with FPGA*

ISE from the Xilinx is used as a design tool in the simulations, and "Virtex-E XCV400E" is chosen as the target device.

Firstly, the MF part and OS-CFAR detector part are coded with Very High Speed Integrated Circuit Hardware Description Language (VHDL) and then Modelsim is used as the simulator for the pre-routed and post-routed design to verify the logic function and timing. After simulations, the circuit of MF with OS-CFAR detector is successfully implemented on the "Virtex-E XCV400E". The slices consumed are 2368 out of the total 4800 in the device. It is about 49.3% of the whole device and the total delay time is 4.877 ns.

VI. CONCLUSION

In multi-path spread spectrum communications, the performance of CA-CFAR detectors is not as good as that in the single-path communications due to the multi target interference and the situation is worse when the number of paths increases.

An OS-CFAR detector is more suitable for multi-path communications, because the OS-CFAR detector with a well-chosen order factor K can avoid the interference caused by multi targets. For M-path communications, if N reference cells are used in the OS-CFAR detector, it has the best performance in P_D and MAT when K equals N-M. Also, using Bubble Sorting, the OS-CFAR detector with K equal to N-M is the easiest to achieve using FPGA implementation, as it requires the least calculation. Thus, in a M-path spread spectrum communication, the OS-CFAR detector with K equal to N-M is the most adequate in terms of performance and complexity.

REFERENCES

[1] D. L. Noneaker, M. B. Pursey, "Rake reception for a CDMA mobile communication system with multipath fading", proceeding *of IEEE* ISSSTA'94, pp98-104, 1994

[2] C. J. Kim, H. J. Lee, H. S. Lee, "Adaptive Acquisition of PN sequence for DSSS communication", *IEEE Trans. Communicaiton,vol. 46, pp.993-996, 1998*

[3] D. Knuth, "The Art of Computer Programming: Sorting and Searching", 2 edition, vol. 3, Addison-Wesley, 1998

[4] L. Zhao, W. X. Liu, X. Wu and J. S. Fu, " A Novel Approach for CFAR Processors Design", *IEEE Trans. Oceanic Engineering, vol.30, pp.900-911, 2005*

[5] J. Linatti, M. Latva-aho " Matched filter acquisition for CDMA systems in multipath channels", *GLOBECOM 9, vol.6, pp.3449-3454, 1998*

[6] K. Chapman, P. Hardy, A. Miller, M. George, "CDMA Matched Filter Implementation in Virtex Devices", *Xilinx application notes,* XAPP212, 2001