

A Novel Gene Detection Method Based on Period-3 Property

Lun Huang, Mohammad Al Bataineh, G. E. Atkin, *Senior Member, IEEE*, Siyun Wang, Wei Zhang

Abstract—Processing of biomolecular sequences using communication theory techniques provides powerful approaches for solving highly relevant problems in bioinformatics by properly mapping character strings into numerical sequences. We provide an optimized procedure for predicting protein-coding regions in DNA sequences based on the period-3 property of coding region. We present a digital correlating and filtering approach in the process of predicting these regions, and find out their locations by using the magnitude of the output sequence. These approaches result in improved computational techniques for the solution of useful problems in genomic information science and technology.

I. INTRODUCTION

THE application of Fourier transform techniques to the research of DNAs and protein sequences results in a very important discovery that is the period-3 property in the protein-coding region. It is convenient to introduce indicator sequences for bases in DNA. For example the indicator for base A is a binary sequence of the form

$$x_A(n) = 100110101000101010...$$

where 1 indicates the presence of an A and 0 indicates its absence. The indicator sequences for the other three bases are defined similarly. Denote the Discrete Fourier Transform (DFT) of a length-N block of $x_A(n)$ as $X_A(k)$, that is

$$X_A(k) = \sum_{n=0}^{N-1} x_A(n) e^{-j2\pi kn/N}, 0 \leq k \leq N-1 \quad (1)$$

The DFTs of $X_G(k)$, $X_T(k)$, and $X_C(k)$ are defined in the same way.

It has been noticed that protein-coding regions (exons) in genes have a period-3 component because of coding biases in the translation of codons into amino acids. This observation can be traced back to the research work of Trifonov and Sussman in 1980 [1]. The period-3 property is not present outside exons, thus can be exploited to locate exons. Taking N to be a multiple of 3 and plot

$$S(k) = |X_A(k)|^2 + |X_T(k)|^2 + |X_C(k)|^2 + |X_G(k)|^2 \quad (2)$$

Then we should observe a peak at the sample value $k = N/3$ (corresponding to $2\pi/3$). Given a long sequence of bases we can calculate $S(N/3)$ for short windows of the data, and then slide the window through the overall sequence. Thus, we can get a picture of how $S(N/3)$ evolves along the DNA sequence. It is necessary that the window length N be sufficiently large (typical window sizes are a few hundreds to a few thousands) so that the periodicity effect dominates the background $1/f$ spectrum [1]. However, a long window implies larger computation complexity in predicting the exon location.

It has been claimed that the period-3 property is due to non-uniform codon usage, also known as codon bias [2]; even though there are several codons which code a given amino acid, they are not used with uniform probability in organisms. For example, base G dominates at certain codon positions in the coding regions [3]. Experiments show that the use of the plot $|X_G(k)|^2$, which depends on base G alone, is often sufficient for revealing the period-3 property, and therefore for the detection of protein coding regions.

However, this method has a lot of limitations. For example, it requires the pre-knowledge of the length of the coding region to perform DFT. In this paper, a novel detection approach is proposed. It uses correlation [4], maximum ratio combination, and filtering. This approach does not require any pre-knowledge of the coding regions, and simulation results show that it can effectively detect the profile of the reading frame for a given genome sequence. This paper is organized as follows. In section II, the system model and underlying theories are described; in section III, the simulation results are analyzed; section IV presents the conclusion of the proposed approach.

II. SYSTEM MODEL AND THEORIES

The system model for the proposed detection scheme is shown in Figure 1.

As we know, the genome sequence includes 4 types of bases, which are A, T, C, G. Before correlation, we must map these bases to symbols. In this paper, we use a complex poly-phase set $\{1, j, -1, -j\}$.

The mapping sequence of genome is correlated with four sequences. These four sequences are composed by using 3 out the 4 types of bases in a period-3 pattern. For example, ATCATC...., can be one of these sequences. Obviously, there are at least four sequences corresponding to 4 base combinations.

Assuming that the input complex genome sequence is $X(n)$,

L. Huang, PhD Candidate; Mohammad Al Bataineh, Ph.D. Candidate; and G. E. Atkin, Ph. D., Senior Member IEEE, Associate Professor; are with the Department of Electrical & Computer Engineering, Illinois Institute of Technology, Chicago, IL 60616; 1-312-567-3417; 1-312-567-8976 Fax (e-mail: lhuang13@iit.edu; albamoh@iit.edu; atkin@iit.edu).

Siyun Wang, PhD candidate, and Wei Zhang, Ph. D., Assistant Professor; are with the Department of Biological, Chemical, Physical Sciences, Illinois Institute of Technology, Chicago, IL 60616; 312-567-3123; 312-567-3494 fax (e-mail: swang26@iit.edu, zhangw@iit.edu).

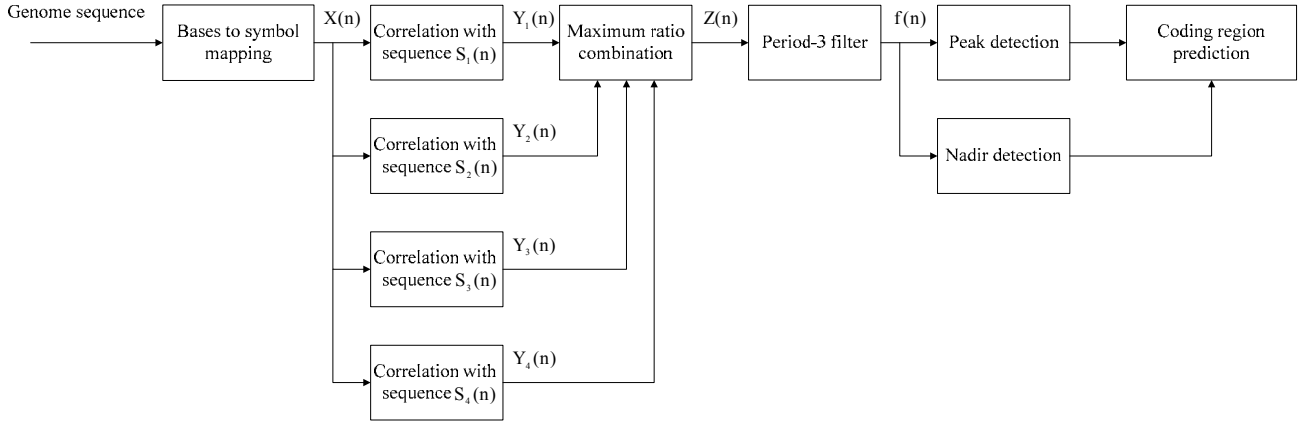


Figure 1. Block diagram for proposed protein coding region detection approach.

the four period-3 sequences are $S_1(n)$, $S_2(n)$, $S_3(n)$, $S_4(n)$, then the correlation outputs are:

$$Y_i(n) = X(n) \otimes S_i(-n) \quad (3)$$

Where ‘ \otimes ’ denotes convolution. After correlation, the 4 output sequences are normalized respectively, and combined using a maximum ratio combination algorithm.

$$Z(n) = \sum_{i=1}^4 \left[Y_i(n) \cdot \frac{|Y_i(n)|}{\sum_{j=1}^4 |Y_j(n)|} \right] \quad (4)$$

Period-3 filtering can be regarded as the sliding window method. A simple period-3 filter has an impulse response

$$W(n) = \begin{cases} e^{j \frac{2\pi}{3} n} & 0 \leq n \leq N-1 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

This bandpass filter is a sequence of length N with minimum stopband attenuation of about 13 dB. The passband is centered at $\omega_0 = 2\pi/3$. A carefully designed digital filter can isolate the period-3 behavior from the background 1/f noise more effectively. We can also use efficient methods to design and implement the filter to reduce computational complexity.

The output of the period-3 filter is

$$f(n) = \sum_{i=0}^{N-1} Z(n-i)W(i), \quad n = N-1, N, \dots, L_x-1. \quad (6)$$

Where L_x is the length of the complex genome sequence input, $X(n)$.

In peak detection and coding region prediction, a window with length L (L is odd in order to make the window symmetric around the center) is applied. When we slide this window on the filter output sequence $f(n)$, at each time $n = k$, we can obtain a maximum value at each time $n=k$, and

$$\text{Max}(k) = \max \{f(k+i-L/2), \quad i=1,2,\dots,L\}. \quad (7)$$

If $\text{Max}(k) = f(k)$, it can be judged that there is a peak at $n=k$.

The steps to determine the optimum value of L based on minimum peak interval variance are as follows.

1. Initiate L_0 and L_1 with $L_x/3$, and set $p_0 = 2$, where L_0

is initial window length, L_1 is current window length, p_0 is original peak number.

2. Use window with length of L_1 to detect the peaks of the filter output sequence $f(n)$.
3. If the number of detected peaks is $p_1 < p_0 + 1$, $L_1 = L_1 - 1$ and go to step 2.; otherwise, set the minimum value of variance $V_{\min} = \infty$.
4. For this p_1 peak distribution, find out the peak interval sequence $\{I_j\}$, $j = 1, 2, \dots, p_1 - 1$.
5. Find out the variance of $\{I_j\}$ with

$$V_1 = \frac{1}{p_1 - 1} \sum_{j=1}^{p_1-1} (I_j - \bar{I})^2 \quad (8)$$

$$\text{Where } \bar{I} = \frac{1}{p_1 - 1} \sum_{j=1}^{p_1-1} I_j.$$

6. If $V_1 < V_{\min}$, $V_{\min} = V_1$, $p_0 = p_1$, $L_0 = L_1$ and go back to step 4.; otherwise, $L_1 = L_0$.
7. In the same ways as step 2. and 3., minimize L_1 for peak

$$\text{number } p_1 = p_0, \quad \text{and } L = 2 \cdot \left\lceil \frac{1}{3} \text{Min}(L_1) \right\rceil + 1,$$

where $\text{Min}(\bullet)$ is the minimization function, and $\lceil \bullet \rceil$ denotes the function that rounds its argument up to the next integer.

It is well known that, for mRNA, synthesis of a peptide always starts from methionine (Met), coded by AUG. The stop codon (UAA, UAG or UGA) signals the end of a peptide. For DNA, U (uracil) should be replaced by T (thymine). In a DNA molecule, the sequence from an initiating codon (ATG) to a stop codon (TAA, TAG or TGA) is called an open reading frame (ORF), which is likely (but not always) to encode a protein or polypeptide. ORF can be combined with gene code books to improve its performance of gene detection.

Furthermore, to improve the coding regions detection, knowledge of the non-coding regions can be used. There are many regulatory sequences in the non-coding regions, then it is possible that the non-coding region can be located with the help of these regulatory sequences in condition that a large enough regulatory sequence set is available. Fake ORF could be eliminated by using this knowledge of the non-coding region.

On the other hand, the approach proposed in this paper can be used to detect non-coding region with only slight changes.

$$\text{Min}(k) = \min\{f(k+i-L/2), i=1,2,\dots,L\} \quad (9)$$

When $\text{Min}(k) = f(k)$, it can be decided that there is a nadir (minimum value point) at $n=k$. The detection window length L can be determined in the same way as that for detecting peaks. Generally, the nadir indicates the absence of period-3 components, and it locates in non-coding regions, so the non-coding region can be found using this approach.

What should be noted is that the proposed approach can detect the protein coding region in both 5'-3' and 3'-5' genome sequence. When a peak appears, it indicates that a coding region exists on this location of either 5'-3' or 3'-5' genome sequence, even both. While a nadir indicates a non-coding region for both 5'-3' and 3'-5' genome sequence.

III. SIMULATION RESULTS AND ANALYSIS

In simulation, the proposed method is applied to both prokaryote and eukaryote genome sequences to detect the profile of coding and non-coding regions.

In case of prokaryotes, a genome segment from prokaryotic bacteria *E. coli* strain MG1655, whose complete genome sequence is available in National Center for Biotechnology Information (NCBI) [5], is used. This segment has 40386 nucleotides.

The length of period-3 sequence $S_i(n), i=1,2,3,4$ is $L_s = 1950$. The period-3 filter is a sequence with length $N = 221$. The peak detection window is with length $L=601$, and nadir detection window is with length $L=1601$.

The detection output is showed in Figure 2. The regions marked by light green colored tags (first row of tags) is the protein coding region for the 3'-5' sequence, and the dark red tags (second row of tags) is for 5'-3' sequence, the blank regions show non-coding regions for both types of sequence. It can be observed that there are some peaks (dark blue lines with a circle on top) in the non-coding region of the 5'-3' DNA sequence of prokaryotic bacteria *E. coli* strain MG1655. This means that there are coding regions in the complementary 3'-5' sequence. The nadir (dark red lines with a cross on top) stems in Figure 2 indicate that there must be a non-coding region around for both 5'-3' and 3'-5' sequence.

In Figure 2, the red line with a cross on top indicate non-coding region for both 5'-3' and 3'-5' DNA sequence, while the blue line with a circle on top indicate coding region in either sequence, or both. Therefore, some accurate detection approaches, such as Hidden Markov Models or gene code books, can be used in the areas between

neighboring red lines to detect coding region, and the blue lines in these areas mark the locations, where the coding region is most likely located. Obviously, the proposed approach will significantly increase the efficiency in detecting coding regions.

Figure 2. also explained why the 1/3 periodicity has even been observed in non-coding regions for prokaryotes. For example, one region is non-coding region for the 5'-3' sequence, but it is coding-region for the 3'-5' sequence. According to [6], the complementary strands are statistically symmetric. Thus, the non-coding region for the 5'-3' will have the same period-3 property as the coding region. It means that the period-3 still works in prokaryotes, and it can be used to detect coding region.

The length of detection window L must be determined by trading off the correctness and resolution. It is decided by the previous algorithm. Narrower detection window will bring about more peaks thus high resolution, but it will also result in more fake peaks at the same time, because it increases the possibility that the detected peak is only a local maximization point instead of a real maximization point indicating the coding region. This scenario is show below in Figure 3, where the length of peak detection window is $L = 201$.

It can be found that some peaks appear in non-coding regions. These peaks indicate local maximization points. The length of nadir detection window can be decided in the same way.

The proposed method can also been used on eukaryote genome. The simulation results for gene T12B5.13 in *C-elegans* (base number 947835 to 949079 in chromosome III, accession number AF100307 [5]), which has 1245 bases and 6 exons, are showed in Figure 4, where $L=81$.

Compared to the statistically optimal null filter (SONF) model-based approach in [7], it can be observed that all of the exons are identified by the proposed approach, while both DFT-based and model-based SONF approaches can not detect the exon between bases 97 and 318. The peaks generated by the proposed approach are also more clear and sharp than the other two approaches. On the other side, the nadirs found by this novel method indicate the approximate locations of introns, which cannot be achieved by those two approaches.

IV. CONCLUSION

In this paper, we have introduced a novel protein coding-region detection algorithm, which is based on period-3 property of coding region. The proposed scheme is more efficient than traditional method, because it waives the need to perform variable length DFT. Compared to DFT and SONF approaches, the proposed approach can detect more coding regions; and it can also be used to detect non-coding regions (introns). By analyzing the simulation result, we have shown that, with the help of ORF analysis, gene library and the regulatory sequence set, it is possible to obtain a relatively accurate prediction of the protein coding-regions in genome.

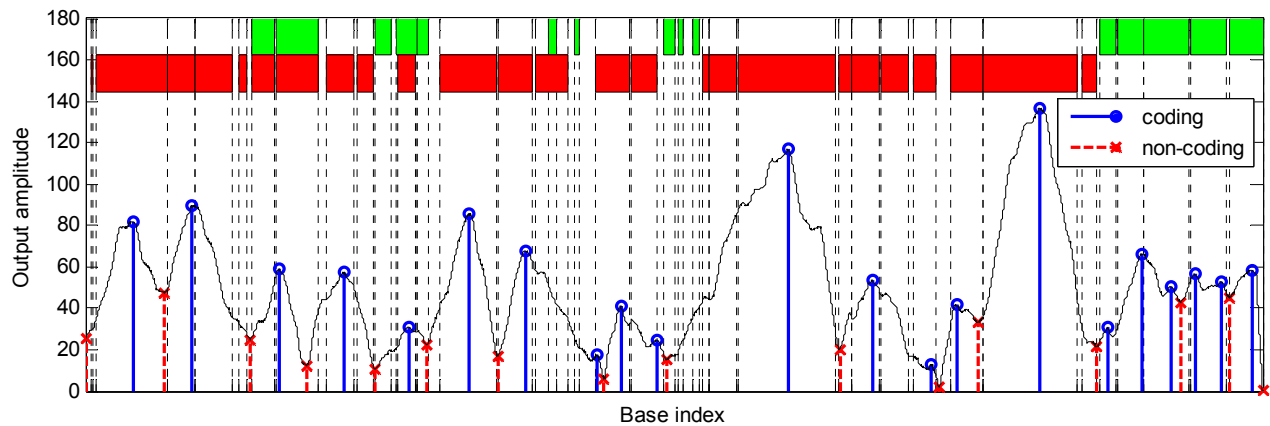


Figure 2. The profile of reading frame for E. coli strain MG1655.

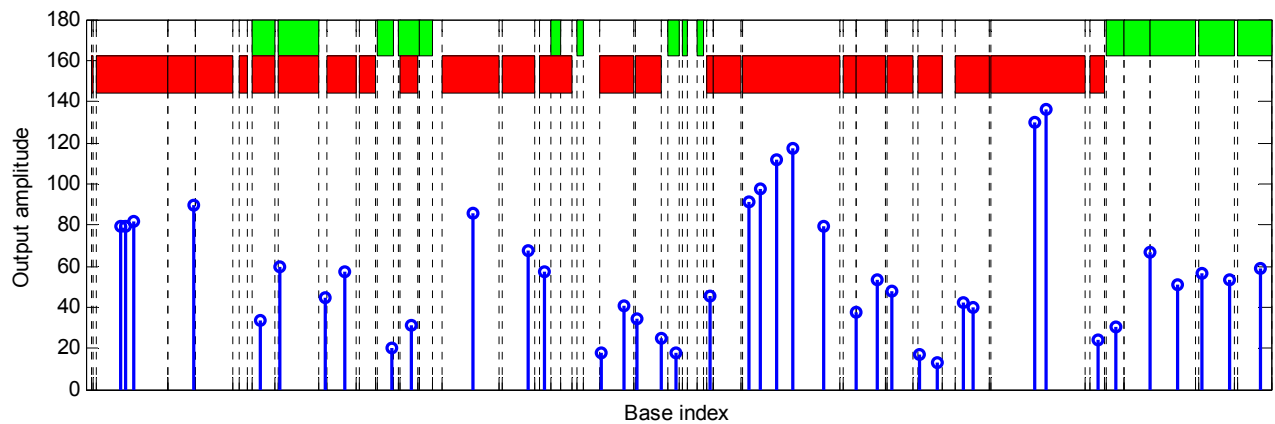


Figure 3. The result of peak detection with narrower detection window for E. coli strain MG1655.

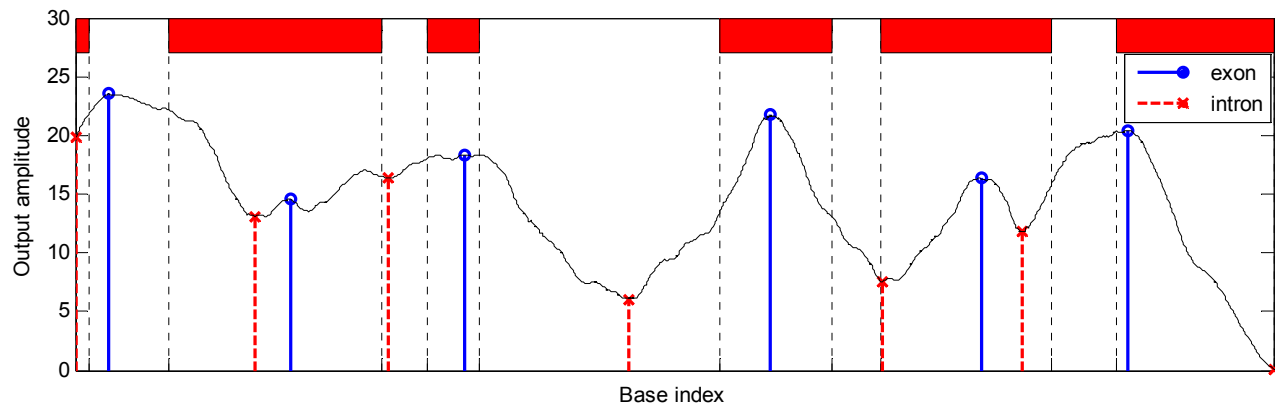


Figure 4. Prediction of protein coding regions of the gene T12B5.13 using the proposed approach.

REFERENCES

- [1] E. N. Trifonov and J. L. Sussman, "The pitch of chromatin DNA is reflected in its nucleotide sequence," *Proc. of the Nat. Acad. Sci., USA*, vol. 77, pp. 3816–3820, 1980.
- [2] Xiu-Feng Wan, Dong Xu, Andris Kleinhofs, Jizhong Zhou, "Quantitative relationship between synonymous codon usage bias and GC composition across unicellular genomes", *BMC Evolutionary Biology*, vol. 4, no. 19, 2004.
- [3] H. Herzel, E. N. Trifonov, O. Weiss, and I. Große, "Interpreting correlations in biosequences," *Physica A*, vol. 249, pp. 449–459, 1998.
- [4] Mohammad Al Bataineh, Lun Huang, Ismaeel. Muhamed, Nick Menhart, and Guillermo Atkin, "Gene Expression Analysis using Communications, Coding and Information Theory Based Models", *BIOCOMP'09 - The 2009 International Conference on Bioinformatics & Computational Biology*, Las Vegas, Nevada, USA, July 13-16, 2009.
- [5] National Center for Biotechnology Information (NCBI) database. Available: <http://www.ncbi.nlm.nih.gov/>.
- [6] Pierre-François Baisnée, Steve Hampson, Pierre Baldi, "why are complementary DNA strands symmetric", *Bioinformatics*, vol. 18, no. 8, pp. 1021-1033, 2002.
- [7] R. Kakumani, V. Devabhaktuni, M. Omair Ahmad: "Prediction of protein-coding regions in DNA sequences using a model-based approach". *ISCAS 2008*, vol. 18, no. 21, pp. 1918-1921, 2008