International Journal of Advanced Computer Research
ISSN (Print): 2249-7277 ISSN (Online): 2277-7970
Volume-5 Issue-19 June-2015

Reliable and energy efficient Nano bacterium communication for optimization solution

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Received: 07-April-2015; Revised: 26-May-2015; Accepted: 28-May-2015

Abstract

Nanonetworks are networks of devices inherently working and communicating at a scale ranging between one and hundreds of nanometers. The motivation behind this nanonetwork and nano molecular communication protocol design to decrease the complexity of the system design and to overcome limitations in terms of size, computation, reliability, storage and energy. In optimization problems classical networking and communication scheme that is applicable in conventional network will not be applicable due to the mentioned limitations in nanonetwork. This paper describes a design of a definite directive molecular communication system using bacterium molecules. In this design Nano nodes encapsulate information into an artificial bacterium. Bacterium propagates through a medium and eventually reached to the receiver. Analytical and simulated numerical results confirm about definite direction of nano molecules which increases reliability of message delivery unlike Brownian motion. We also proposed artificial nano bacterium architecture, storage and optimum operational parameter values required in an energy efficient way.

Keywords

Nano molecular communication network, nano machine communication, bacteria foraging optimization, BFO optimal parameters.

1. Introduction

Nano communication is the exchange of information on the nanoscale and it is at the basis of any wireless interconnection of nanomachines in a nanonetwork.

Due to its size in nanoscale there are significant challenges in terms of storage, processing power reliability and protocol design. So instead of traditional network communication, there is an urge to develop new innovative algorithms which can operate at a nano scale level with low processing power, storage requirement with higher reliability. On the other hand, Optimization is a commonly encountered mathematical problem in all engineering disciplines. It literally means finding the best possible/desirable solution.

Optimization problems are wide ranging and numerous, hence methods for solving these problems ought to be, an active research topic. Optimization algorithms can be either deterministic or stochastic in nature. Past methods to solve optimization problems require enormous computational efforts, which tend to fail in computational scaling as the problem size increases [7]. This is the motivation for employing bio inspired stochastic optimization algorithms as computationally efficient alternatives to deterministic approach. In this paper, we are proposing Artificial Bacteria Foraging Optimization Algorithm to define artificial nano molecular communication behavior after analyzing pros and cons of it and also with respect to other bio inspired algorithms. We also studied the influencing parameters which are required to simulate this behavior in real time scenarios. We also defined optimal values or range of values for these influential parameters so that it can scale out during the actual implementation.

The scope of study is to understand and realization of chemotaxis communication behavior [1] [2] (by optimizing set of related defined parameters) between source nanonode and receiver nanonode using bacterium nano molecular communication. We have proposed energy efficient [8] bacterium architecture, storage and optimized operational parameters that should be considered during artificial bacterium architecture and chemotaxis behavior design.

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2. Nano molecular Communication

2.1 Communication Architecture

Molecular communication (MC) is a promising communication paradigm for nanonetworks, where the transmission and reception of information are realized through molecules, as it naturally occurs within the living organisms. Chemotaxis based communication is broadly classified under walkway based communication architecture [4][6]. It's used to communicate between medium to long range distances [5] and the direction of movement is guided by increasing or decreasing gradient of chemotaxis substance in the medium. Positive chemotaxis occurs if the movement is toward a higher concentration of the chemical. However, negative chemotaxis occurs if the movement is in the opposite direction.

2.2 Artificial Bacteria Structure

Generic nano machine architecture has been proposed by Ian F. Akyildiz, Fernando Brunetti and Cristina Blazquez in their published paper [3]. Bacteria based nano machine physical architecture is extended from generic nano machine architecture to support and perform swarming activities during each phase of bacteria life cycle. Below is the proposed physical architecture of artificial bacterium.

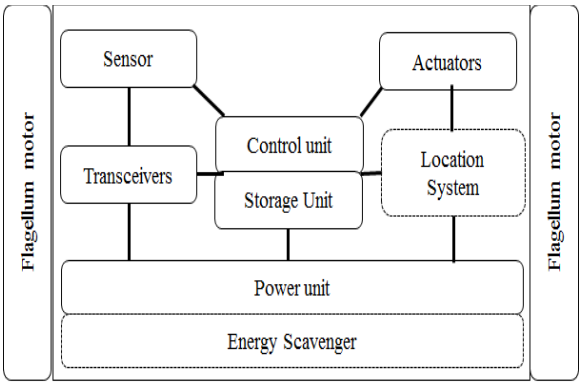

Fig 1: Artificial bacteria structure

Control Unit: This is considered as a nucleus of the system. This is the central processing unit and considered as a brain of each bacterium. It contains all instructions in a precompiled format for which the bacteria are intended to perform. This unit component is having the decision making power to control the motion of bacteria (Tumble and Swims phase).

Communication Unit: Communication between nano-machines is needed to allow them to realize more complex tasks in a cooperative manner. This unit communicates with the environment and interact with the system with predefined communication message structure (e.g. to let neighbour bacterium know about the current position) or by principle wise working behaviour (e.g. Spraying anti-pollution agents, anti-fire chemical).

Power Unit: This unit is aimed at powering all the components of the nano-machine. The unit will be able to scavenge energy from external sources such as light, temperature and store it for a later distribution and consumption. Inside bacterium, internal source (battery) or external sources such as photoelectric volts can be considered as a source of power.

Sensor and actuators: These components act as an interface between the environment and the bacterium nano-machine. Several sensors and/or actuators can be included in a bacterium as per the operational behaviour, e.g., Temperature sensors, chemical sensors, clamps, pumps, motor or locomotion mechanisms.

Flagellum motor unit: It can able to spin clockwise or anticlockwise based on dynamic number of spinning units. Spinning of flagellum motor controls chemotactic behaviour of bacteria (Swim and Tumble).

3. Artificial Bacterium Lifecycle Model

3.1 Lifecycle phases

Bacteria lifecycle is comprised of following phases mentioned by L. Kaur, M.P Joshi in the published paper [2]. Chemotaxis, Swarming, Tumbling, Reproduction and Elimination/ Dispersal are major life cycle phases of bacteria. Reproduction and Elimination dispersion stages, phases are not much more relevant in artificial BFO execution as total number of injected bacteria into the system is constant. Bacteria can only die due to lack of energy or faulty hardware. Bacteria will die for battery driven energy source if battery power decays completely before reaching to sink. In case photoelectric or chemically generated energy if the energy scavenger unit fails, then bacteria will die after a certain time in the system. In Elimination

phase bacteria should able to identify a way to move ahead into instead of locking itself into local minima. A mechanism has been proposed based on similarity function execution below.

3.2 Artificial Adaptive Bacteria Foraging Optimization Algorithm

Below the activity diagram of artificial adaptive BFO algorithm inspired by bacteria foraging algorithm proposed in [2].

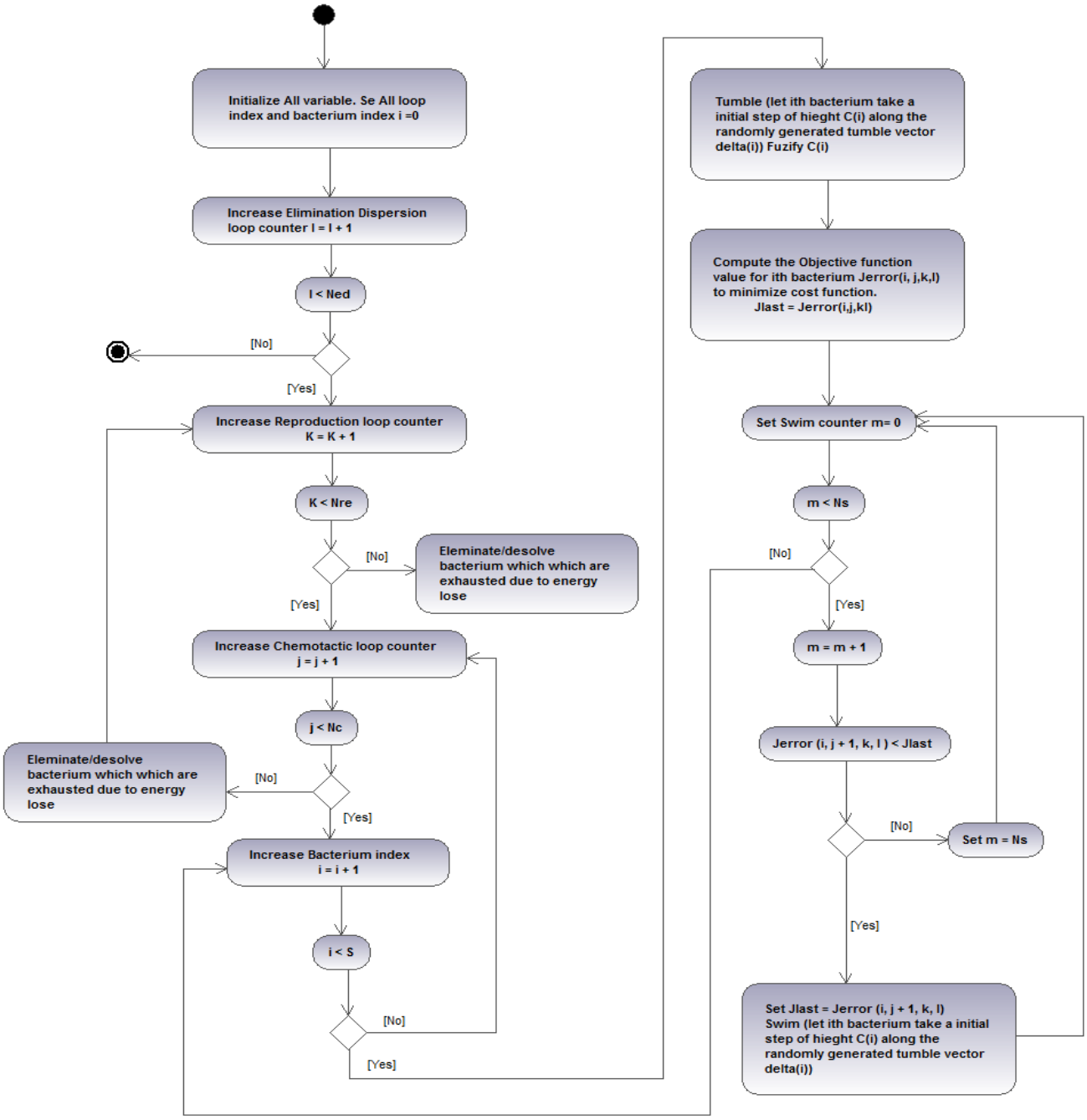

Fig 2: Activity diagram of artificial adaptive BFO algorithm

4. Simulation Results

4.1 Experiments

The Java based simulation engine has been proposed and initial version has been implemented to experiment on bacteria lifecycle and its chemotaxis behaviour. Simulator execution is based on map reduce parallel processing algorithm where multiple homogeneous (different bacterium cluster/colony of same chemotactic behaviour type) or heterogeneous executions (different bacterium cluster/colony of different types of chemotactic behaviour) can be done in parallel. In this experiment we assumed that all bacteria are homogeneous in nature. There is no collision within bacterium or with external elements. No external influences can change the default lifecycle behaviour of bacteria other than chemotaxis.

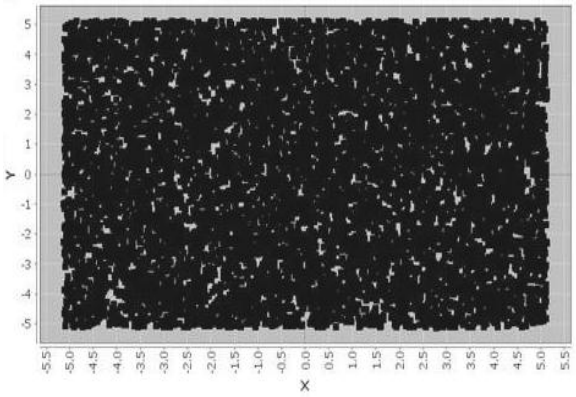

Fig 3: At Initial Stage (Bacterium initialized at random position)

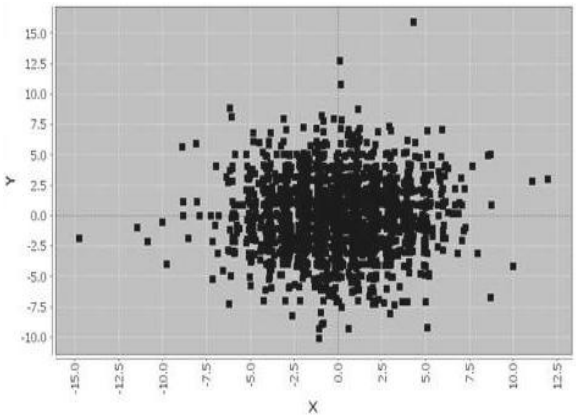

Fig 4: Bacterium converges to the destination after execution

4.2 Performance Analysis

Parameters:

Number of Bacteria: This parameter stated initial size of artificial bacteria injected into the system.
Viscosity: It describes a medium internal resistance to flow and may be thought of as a measure of medium friction. This parameter stated the medium in which bacteria injected. Based on medium bacteria motion length will differ.

Cost Function: Through the simulation each bacteria will try to minimize Rastrigin Cost function.
Energy decay rate is the rate by which the artificial battery will decay.

Number of chemotactic steps (Nc) define the termination criteria for the algorithm after a finite number of steps.

Below is the table containing the default value set for execution.

Table 1: Default execution parameter value set ABFO has been executed 10 times and the results are averaged for each scenario execution below

Number of Bacteria	5000
Viscosity	Default/ Air
Cost Function	Rastrigin Cost Function
Energy Decay Rate	0.05
Chemotactic Step (Nc)	20

Scenario – 1 - Default medium

Table 2: Execution parameter value set of Default medium

Bacterium = 5000, visocity = Default,RastriginCostFunction, Energy decayRate = 0.05, Nc = 20	
Dimension	2d Range [-5.12,5.12]
Bacteria Left in System	4681
Bacteria Within Range	3543
Energy Lost	108
Chemotactic Step Lost	225

The algorithm has been executed 10 times and averaged with Bacteria size = 5000, in the default medium (viscosity = 0.0 units) with linear energy decay rate = 0.05 and with chemotactic step size = 20.
After execution of the algorithm in default medium total bacteria left in the system is ~ 4681. Within it ~3543 numbers of bacteria can reach the source or reach nearer to the source. After completion of

execution ~108 numbers of bacteria is failed to make further move and dies down due to loss of energy. 225 numbers of bacterium are failing to move due to exhaustion of the chemotactic step of the algorithm or some of them may stuck into local minima which can't converge into global minima.

Scenario -2 – Air medium

Table 3: Execution parameter value set of Air medium

Bacterium = 1000, visocity = Air,RastriginCostFunction, Energy decayRate = 0.05, Nc = 20	
Dimension	2d Range [-5.12,5.12]
Bacteria Left in System	4658
Bacteria Within Range	3562
Energy Lost	113
Chemotactic Step Lost	217

The algorithm has been executed 10 times and averaged with Bacteria size = 5000, in air with linear energy decay rate = 0.05 and with chemotactic step size = 20.

After execution the algorithm in default medium total bacteria left in the system is ~ 4658. Within it ~3562 numbers of bacteria can reach the source or reach nearer to the source. After completion of execution ~113 numbers of bacterium are failed to make further move and dies down due to loss of energy. 217 numbers of bacterium are failing to move due to exhaustion of the chemotactic step of the algorithm or some of them may stuck into local minima which can't converge into global minima.

Impact on Change in Medium Viscosity of Default medium is 0.0 Kg/m.s and Viscosity of Air 1.8 x 10-5 kg/m.s. From Scenario -1 and Scenario -2 we observed that with the change in medium from Default to Air number of bacteria left in the system get reduced by ~ 23 numbers. In higher viscous medium Bacteria have to spend more Energy and it requires higher steps to reach to the source. As total Energy (1 unit) and its decay rate (0.05 unit) is constant, from Scenario -1 to Scenario -2 higher numbers of bacterium dies due to energy loss. In execution, the difference is ~ 5 numbers. Ns is the chemotactic step size after that algorithm stops. It defines the termination criteria for ABFO algorithm. The bacterium dies down due to exhaustion of chemotactic step decreases with the medium change. The difference is ~ 8 numbers. There can be another possibility for chemotactic step exhaustion. Some of Bacterium can stick into local minima instead of converging into global minima. But these numbers are very less with compare to total bacterium into the system.

Execution -1: *Varying chemotactic step size (Nc) with constant energy decay rate. S= 5000, Medium = default.*

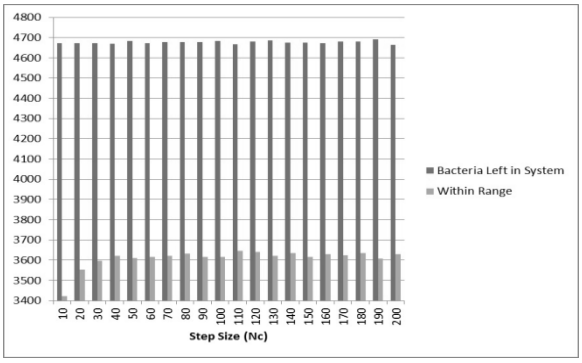

Fig 5: Execution -1 Execution Result Graph

Table 4: Execution parameter value set varying Nc

Step Size (Nc)	Bacteria Left in System	Within Range
10	4673	3423
20	4672	3553
30	4671	3598
40	4669	3621
50	**4684**	**3612**
60	4673	3615
70	4678	3623
80	4676	3632
90	4677	3615
100	4684	3617
110	4666	3646
120	4681	3640
130	4685	3622
140	4674	3636
150	4674	3617
160	4672	3630
170	4679	3625

The algorithm has been executed five times and took average for each chemotactic step size (Nc) with constant energy decay rate = 0.05 for each step. With increasing step size Bacterium within system remains more or less are same. It's not leave system either.

On an average 2% bacterium are lost due to energy and ~ 4.3 % bacterium dies due to exhaustion of chemotactic steps. To increase chemotactic step size (Nc) number of bacteria reaches towards Range as it gets more time to traverse in defined medium.

Execution-1 implied that increase of step size (Nc) means longer duration of algorithm execution, which required large CPU cycle, processing power and energy. Form execution results, it's clear that with increasing steps we are not getting noticeable improvement in overall execution results. The optimum size of Nc = 50 so that It's does not kill CPU cycle, processing time and energy.

Execution-2*:* Varying energy decay rate with respect to constant step size = NC = 20, S= 5000, Medium = default

Table 5: Execution parameter value set varying decay rate

Energy Decay Rate	Bacteria Left in System
0.02	**4970**
0.04	4818
0.06	4389
0.08	3006
1	1266
0.12	193
0.14	10
0.16	0
0.18	0
0.2	0
0.22	0
0.24	0
0.26	0
0.28	0
0.3	0

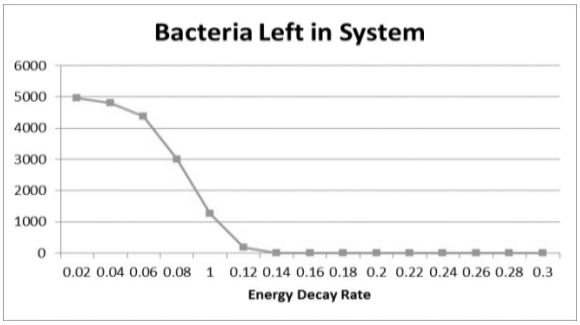

Fig 6: Execution -2 Execution Result Graph

The algorithm has been executed five times and took the average for varying the decay rate (+0.02 unit) with constant energy step size = 20 for each step. It has been observed that with increase energy decay rate, the number of bacteria dies out almost at an exponential rate.

Execution–2 implied that if energy decay rates of each bacteria is less than 2% of total energy for each move, then greater than 90% bacterium will not leave the system because loss of energy. If energy decays of each bacterium are greater 14% of total energy for each move, then no bacteria will converge into source and all will eventually die due to loss of energy.

Execution–3*:* Varying Bacteria movement increment size (Ci) rate with respect to constant step size = NC = 20 and energy decay rate = 0.05, S = 5000, Medium = Default.

Table 6: Execution parameter value set varying Ci

Bacteria movement increment size (Ci)	Bacteria Left in System	Energy Lost	Chemotactic Exhaust
0.01	4671	111	222
0.03	4669	109	224
0.05	**4682**	**105**	**228**
0.07	4686	105	212
0.09	4670	108	217
0.11	4674	108	220
0.13	4667	108	224
0.15	4679	108	218
0.17	4674	108	218
0.19	4688	109	221
0.21	4676	107	227
0.23	4681	106	218
0.25	4681	107	233
0.27	4675	111	215
0.29	4673	111	222

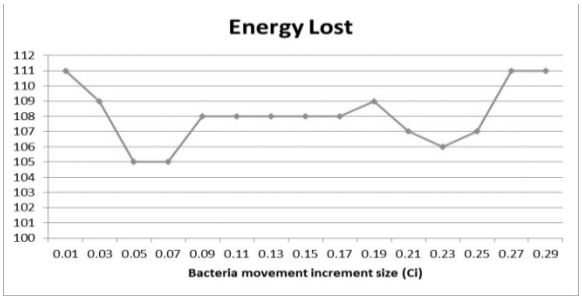

Fig 7: Graph of Bacteria dies rate due to energy loss

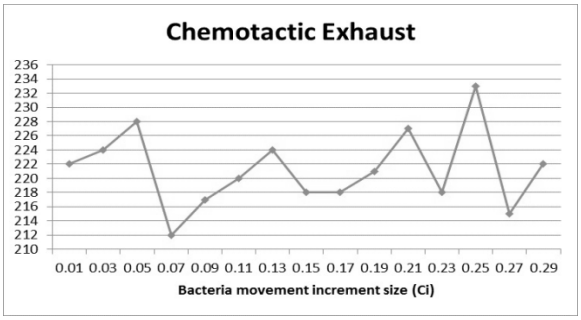

Fig 8: Graph of Bacteria dies rate due to chemotactic exhaust

The algorithm has been executed five times and took the average for varying Bacteria movement increment size (Ci) (+0.02) with constant energy decay =0. 05 for each move, and chemotactic step size = 20. Observed that with increased bacteria movement increment size (Ci), Bacterium left in the system is decreased. The bacterium dies out due to Energy lost is increased. The bacterium dies out due to chemotactic exhaust is more or less constant.

Execution -3 implied that, with increased Bacteria movement increment size (Ci), for each move bacteria traverse the longer distance. If bacteria are in running stage, this will help to converge into the sink quickly, but if bacteria are in a tumble state (higher probability) it may have to traverse longer steps to find the right direction. This event introduces restlessness among bacterium which in turn causes Energy lost to a large extent. That's why we can see with increase movement size, number of bacteria dies out due to energy lost is also higher. Similarly, if we choose small movement size bacteria energy will dies out quickly as it had to traverse many steps to reach the sink. These will again put the system in unstable mode. An optimal value (0.05) can give maximum stability and accuracy to the system in a given condition.

4.3 Storage requirement

To perform a basic traversal operation from source to sink it should hold storage space two bits to represent 0, 1 or 2. 1 indicates a positive chemotactic change in gradient in current move and 0 indicates no change in gradient and 2 indicate a negative change in gradient. Rest, Information storage should be decided based on the nano machine physical storage capacity. Storage capacity should be more if individual bacteria need to keep current locomotive information. In case bacteria got stuck into local minima. K–means nearest neighbour algorithm (k=3) can be used to determine that. In that case bacteria will broadcast its current locomotive information to nearest bacterium within range. Upon receiving the request nearest bacterium will reply back with single bit 0 (no change /negative change) or 1 (positive change) based on similarity function computation (e.g. Distance function). If minimum one neighboring bacteria are in a better position (similarity function is above threshold) than requesting bacteria will tumble to find the best position.

4.4 Energy and Computation requirement

Bacteria spend most of their energy during the chemotaxis phase (tumble and swim). By effective use of adaptive swim the length (Bacteria movement increment size (Ci)) major energy can be saved. In above experiment we have seen that effective Ci value varies within 0.02 to 0.05. Each spin of flagellum motor will swim bacteria 0.01 units. If bacteria continue to move into positive direction instead of computing the chemotactic gradient on each move, Ci (0.02 <= Ci <= 0.05) values can increase gradually by spinning the motor. Say, in first move bacteria swims 0.01 units with single motor spin. If the chemotactic gradient is still positive bacterium will spin twice for the next Ci cycle (Ci = 0.02). If any point of time bacteria tumbles Ci values will be re-initialize to 0.02. This adaptive run length algorithm will definitely reduce the instability, computational power and improve the convergence rate and time to the sink.

5. Application Areas

In life science targeted drug delivery into living animal is the critical application to be considered. Today steroids are injected into a living body which produces side effects. Intelligent bacterium can be injected into living body which transmitted to the target location and delivers drugs directly into the affected areas. To find out source of chemical of fire hazards this approach can be considered. The Nano bacterium will be injected into an environment which will reach and takes preventive measures on the target. Numerous optimization applications including pollution detection in the long tunnel, part of environmental science, soil composition detection, health monitoring of root variables, fruits healing in agricultural science are major application areas to be considered.

6. Conclusions

In this work we have analysed the algorithmic complexities for optimization problems using nature inspired ABFO algorithm. With proposed basic hardware designs based on artificial bacteria behaviour. Work focused on optimum values of parameters of ABFO algorithm which are key drivers of the algorithm. Due to limited storage and energy requirement, we proposed low computational hardware based adaptive swim algorithm to minimize computation and energy requirement. We have analysed minimal storage requirement and proposed algorithm based on similarity function to address issues of global convergence.

Acknowledgement

I am extremely grateful to Dr. Parama Bhaumik, Asst. Professor, Department of Information Technology, Jadavpur University for providing me the needed guidance to complete this work with her invaluable suggestions and necessary information in this field.

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