Ant Colony inspired Self-Optimized Routing Protocol based on Cross Layer Architecture for Wireless Sensor Networks

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Abstract: - Nowadays, wireless sensor networks (WSNs) are becoming increasingly beneficial, worthwhile and a challenging research area. The advancements in WSN enable a wide range of environmental monitoring and object tracking applications. Moreover, multihop (node by node) routing in WSN is affected by new devices constantly entering or leaving the network. Therefore, nature inspired self-maintained protocols are required to tackle the problems arising in WSN. We proposed ant colony stimulated routing, which shows an outstanding performance for WSNs. In this manuscript, a cross layer design based self-optimized (ACO) routing protocol for WSN and the results are presented. Link quality, energy level and velocity parameters are used to discover an optimal route. The signal strength, remaining power and timestamp metrics are trade in from physical layer to network layer. The emitted decision through the WSN discovery will establish the optimal route from source to destination. The adopted cross layer architecture helps ACO in improving the overall data delivery ratio; especially in the case of real time traffic.

Key-Words: - Ant Colony Optimization, Cross Layer, Energy, Multihop, Packet Reception Rate, Routing, Velocity, Wireless sensor Network

1 Introduction

Wireless communication plays a significant role in telecommunication sector and has huge importance for the future research. Wireless communications enables many new applications for sensing and monitoring systems. Some infrastructure free networks like WSN serves an imperative task in monitoring. With the passage of time new gadgets and software advancements are becoming available to end-users on a frequent basis. The stated fast growth and the huge number of devices in the network make WSN more and more complex. The deployment area for WSNs is mostly out of the human reach. The above mentioned challenges, such as growing complexity and unreachable maintenance need new solutions.

The new self-maintained mechanism can maintain the features of WSNs such as multihop routing and dynamically environmental changes in a completely autonomous mode. In order to address autonomous capability for multihop WSNs, it has been visualized that self-maintained network applications can understand the operational objectives of the network. Additionally, probabilistic methods that provide scalability can be found in nature and adapted to technology.

Towards this vision, it is observed that various biological principles are capable to overcoming the above adaptability problems. The area of bio-inspired network engineering has the most well known approaches which are swarm intelligence (ANT Colony, Particle swarm), AIS and intercellular information exchange (Molecular biology)[1-4]. WSN routing algorithms based on ANT Colony Optimization (ACO) have been presented in the last few years, such as [5], Sensor-driven Cost-aware Ant Routing (SC), the Flooded Forward Ant Routing (FF) algorithm, and the Flooded Piggybacked Ant Routing (FP) algorithm [6], Adaptive ant-based Dynamic Routing (ADR) [7], Adaptive Routing (AR) and Improved Adaptive Routing (IAR) algorithm [8], and E&D ANTS [9].

The problem of the previous approaches is that the selected shortest path might not be a minimum energy cost route. Some other works concentrate on decreasing the energy consumption by replacing the hop-count routing with minimum energy routing. They compute a minimum-energy path for packet delivery in a multi-hop wireless network. However, the nodes on this path will get depleted soon [10]. Radhika D.Joshi [11] given an idea about combination of least hops and minimum remaining energy.

This manuscript present a novel architecture by implementing the most well known and successful approaches. ACO method is utilized for the optimum route discovery in multihop WSN. Standard ACO is very complex and heavy for WSN. Consequently, we come up with an ACO that can perform better optimization for WSN in terms of less load, less energy consumption and high delivery rate.

Generally, the ACO algorithm is agent based [12] as forward ant (FA), backward ant (BA), search ant (SA) and data ant (DA) agents as shown in Figure 1.

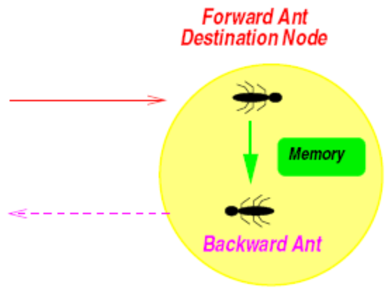

Fig. 1 Arrived at the destination node the forward ant is transformed into a backward ant, which inherits from the former all its memory [13].

Standard ACO algorithm is very complex and heavy for WSN. Consequently, we come up with an ACO algorithm that can perform better optimization for WSN in terms of less load, less energy consumption and high delivery rate. Under BIOSARP, ACO is based on only two types of ant agents, which are, search ant (SA) and data ant (DA) agents. While data forwarding, the node first calls the DA. DA will select the optimal node based on the pheromone value stored in neighbour table. DA will move hop by hop on the base of pheromone values for neighbouring nodes until the destination as shown in Figure 2. The agents will work in a decentralized way to collect data on individual nodes and carry data to the required destination through multihop communication.

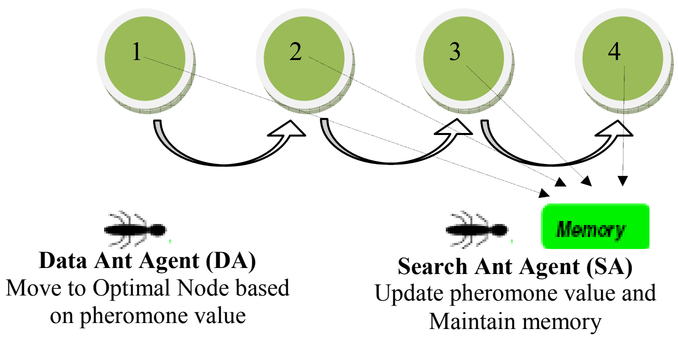

Fig. 2 BIOSARP ACO mechanism based on Data Ant (DA) and Search Ant (SA) agents

While selecting optimal node, if DA could not find the entry in the neighbour table, it will invoke SA as given in Figure 2. The SA will search for new nodes and calculates their pheromone value through the probabilistic rule. The pheromone value is based on three metrics, which includes first the packet deadline (velocity). The wireless link quality at the physical layer is study to calculate the transmission between sensor nodes. In addition, the remaining power is estimated to spread all traffic load distribution over the network during path forwarding to the destination. Every ant agent is generated with a sequence ID and also is set with maximum time to live (TTL) as narrated in Figure 3. By the help of assigning sequence ID, sensor node will not accept reappearance of the same ant agent to avoid routing cycles. If an ant agent does not reach its destination before a given TTL value, the ant agent is destroyed.

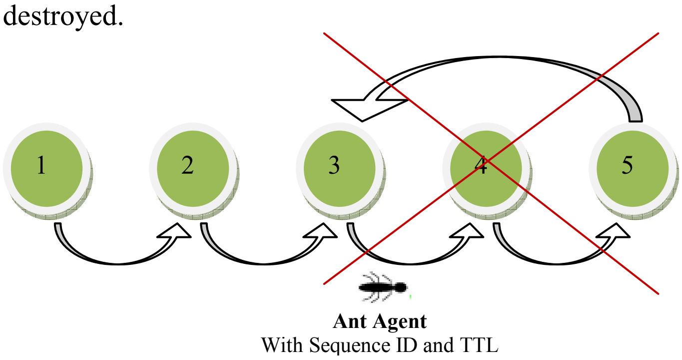

Fig. 3 BIOSARP mechanism to avoid routing cycles

Furthermore, the recent work on WSNs reveals that cross layer design technique results in significant improvement in term of energy conservation in WSNs. This requires that a routing protocol of WSNs should apply cross-layer design strategy [14]. The given biological inspired algorithm is enhanced with cross layer architecture to attain more robust decision. The signal strength, remaining power and timestamp parameters have been taken from the physical layer to the network. By assigning the above mentioned metrics to the ACO process running on the network layer allows an ultra effective optimal route for WSNs.

2 Related Research

2.1 Outline of Ant Colony Optimization

Dorigo et al [5] proposed the first ant colony algorithms as a multi-agent approach to difficult combinatorial optimization problems like the traveling salesman problem (TSP) and the quadratic assignment problem (QAP), Minimum Weight Vertex Covering Problem [15, 16], and later introduced the ACO meta-heuristic by Dorigo et al [5].

There are two types of ants applied in the algorithms, forward ants and backward ants. Forward ants, whose main actions are exploring the path and collecting the information from the source nodes to destination node, have the same number as the source nodes. The paths that forward ants travel will construct a tree when they merge into each other or reach the destination and data is transmitted along the tree paths. There are two key factors that conduct the movement of the forward ants: one is pheromone trails that are deposited along the edges, and the other is the nodes potential which provides an estimate of how far an ant will have to travel from any the node to either reach the destination or to aggregate data with another node. Whereas the backward ants, traveling back from destination node to source nodes contrary to the forward ants, perform their uppermost function of updating the information of their pass-by nodes.

ACO algorithms are a class of constructive meta-heuristic algorithms that mimic the cooperative behavior of real ants to achieve complex computations and have been proven to be very efficient to many different discrete optimization problems. Many theoretical analyses related to ACO show that this optimization can converge to the global optima with non-zero probability in the solution space [17] and their performance have greatly matched many well-studied stochastic optimization algorithms, for example, genetic algorithm, pattern search, GPASP, and annealing simulations [5].

2.2 Overview of ACO Based Routing Algorithms in WSN

Sanjoy Das et al have given an on-line ACO algorithm using AntNet techniques for MSDC [18] which has been formalized to be a typically Minimum Steiner Tree problems. They also have proposed an improved algorithm by adding another type of ants, random ants, analogous to a newspaper deliverer, whose main task is to disperse information gathered at the nodes among other neighboring nodes. Practically, simulation results also show that their algorithms are significantly better than address-centric routing. In these proposed algorithms the forward ants normally spend a long time. There is a bug of dead lock in their algorithms. In their improved algorithm, a large number of random ants are needed.

In [5] the authors propose a new idea of keeping the information by all sensor nodes of their own. By this even in the absence of global processing the nodes still can work on their own information. This still has the drawback of broadcasting in the initialization phase, which consumes lots of energy at the beginning of the network deployment.

Zhang et al. [6] proposed three ant-routing algorithms for sensor networks. The SC algorithm is energy efficient but suffers from a low success rate. The FF algorithm has shorter time delays; however, the algorithm creates a significant amount of traffic. Despite high success rate shown by the FP algorithm but is not energy efficient.

An Adaptive ant-based Dynamic Routing (ADR) algorithm using a novel variation of reinforcement learning was proposed by Lu et al. [7]. The authors used a delay parameter in the queues to estimate the reinforcement learning factor.

Karaboga [19] proposed a novel approach for WSN routing operations. Through this approach the network life time is maximized, for discovering the shortest paths from the source nodes to the base node using an evolutionary optimization technique. The research has also been implemented on the PIC® series of microcontrollers, specifically the PIC12F683.

Aghaei et al [8] proposes two adaptive routing algorithms based on ant colony algorithm, the Adaptive Routing (AR) algorithm and the Improved Adaptive Routing (IAR) algorithm. To check the suitability of the ADR algorithm in the case of sensor networks, they modified the ADR algorithm (removing the queue parameters) and used their reinforcement learning concept and named it the AR algorithm. The AR algorithm did not result in optimum solutions. In IAR algorithm by adding a coefficient, the cost between the neighbor node and the destination node, they further improve the AR algorithm.

Wen et al [9] proposed a dynamic adaptive ant algorithm (E&D ANTS) is based on Energy and Delay metrics for routing operations. Their main goal is to maximize the network lifetime while minimizing propagation delay by using a novel variation of reinforcement learning (RL). E&D ANTS results was evaluated with AntNet and AntChain schemes.

2.3 Comparison between Ant Based Routing Mechanisms

Comparison of the most recent ANT based routing in WSN: SC and [19] depends on the energy metric whereas FF based on delay. IA and IAR is the modification of ADR which used a delay parameter in the queues to estimate reinforcement learning factor. In FP they combine the forward ant and data ant to enhance the success rate. E&D ANT based on energy and delay metrics for routing operations.

In our proposed algorithm, the best values of velocity, PRR and remaining power mechanism [20] are used to select forwarding node because velocity alone does not provide the information about link quality. The best link quality usually provides low packet loss and energy efficient [21]. Another novel feature is the remaining power parameter to select the forwarding candidate node.

2.4 Comparison between Cross Layer based Mechanisms

During the previous decade, many energy efficient network routing protocols have been proposed for sensor networks. Earlier routing schemes involve direct communication protocols which facilitate direct communication between the source node and the base station. Therefore, for scenarios where the base station is quite a distance away from the source node, there is excessive usage of energy resources, ultimately resulting in a complete drainage of power. Such routing schemes are successful only where sensor nodes are near enough to the base station [22].

In [10, 23], an Adaptive NAV-Assisted Routing (ANAR) protocol is proposed to alleviate the network congestion based on the cross-layer information. The ANAR scheme utilizes the existing information from the Request-To-Send (RTS) and the Clear-to-Send (CTS) packets within the contention based MAC scheme.

In [24], based on the received signal strength, they can forecast if the mobile node will move out of the transmission scope soon, and change to the next node before the link broken. It collects the MAC layer residual bandwidth, link delay and battery remaining energy information, then utilizes cross-layer communication to change pheromone value depending on the weight value of QoS parameters, to reduce packet loss and select an optimal path.

[22] proposed a cross-layer architecture using MAC and Routing layer. The cross layer architecture implemented in this research is defined by the interaction of 802.11 MAC protocol and the Dynamic Source Routing protocol. The cross-layer architecture implemented in this work will be able to reduce routing overheads, by reducing the route management processing performed by the DSR protocol in most scenarios. The authors have implemented the 802.11 MAC extensions in Network Simulator-2 (NS-2) that stores the last signal strength received from all neighboring nodes. In addition, they also modified the 802.11 MAC layer to send a message to the upper layer in case there is a loss of communication but the destination node is still within the transmission range.

In [25] the author has proposed a local routing protocol for WSN. In their protocol they utilized the cross layer concept to attain an optimal decision on single hop bases. The signal to noise ratio for evaluating packet reception rate and energy values are called from the physical layer to the network layer.

3 Methodology

System design deals mainly with the development of state machine and flow chart diagram of the sections as power and neighbor management as shown in Figure 4. Routing management will be dependent mostly on forwarding metric calculations. If any error occurred in this state, the generated error will be handled by the routing problem handler as elaborated in Figure 5.

Further onwards the most important state in this routing mechanism is neighbor management. Selection of better neighbors will be handled by this state. Common functions in the neighbor management state are neighbor table maintenance, neighbor discovery, insert new neighbor, neighbor replacement, etc as exposed in Figure 6.

The optimal route discovery is tackled by ACO. Routing decision will achieved by the probabilistic decision rule described in [19]. Two parameters delay and battery remaining are used in [19] while acquiring optimal decision.

Our proposed mechanism BIOSARP is based on three metrics as, velocity, PRR and remaining power mechanism as given in Table 1.

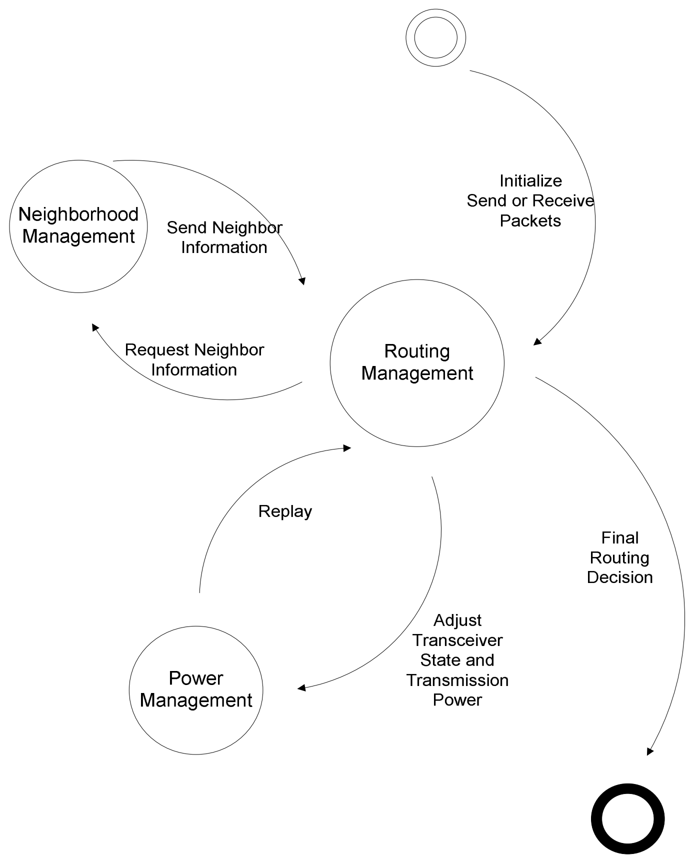

Fig. 4 System Diagram

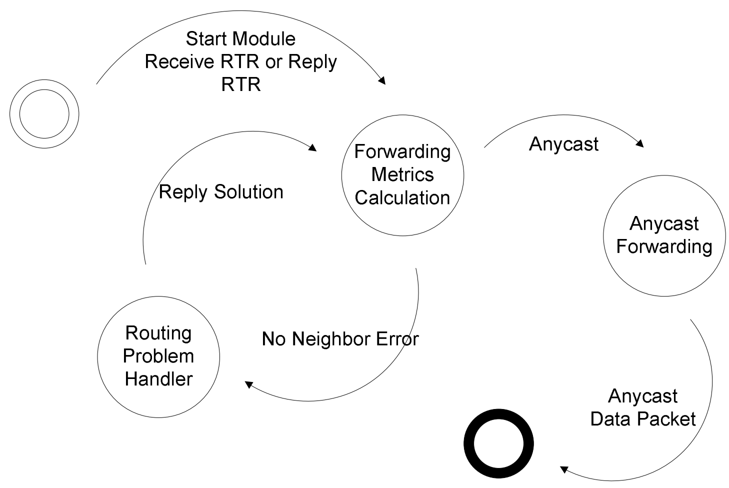

Fig. 5 Routing Management

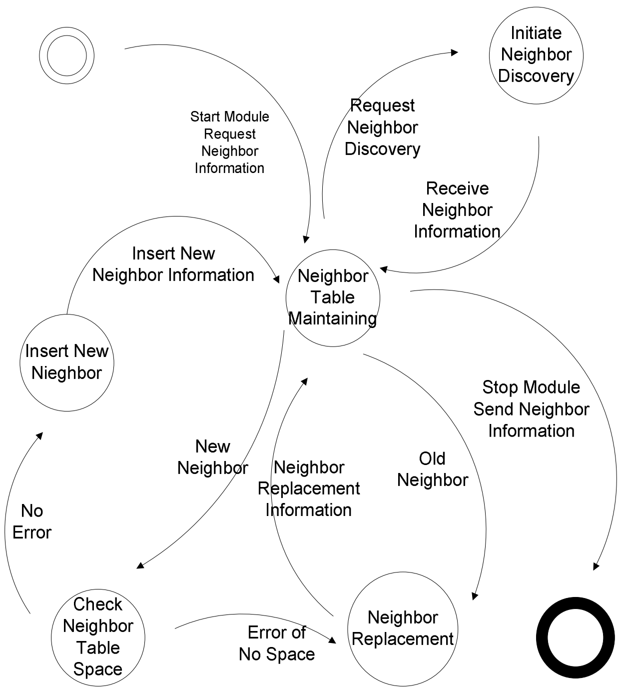

Fig. 6 Neighbor Management

Table 1. Routing Metrics

	Velocity (End2End Delay)	Energy	Link Quality (PRR)
Node 1	τ^1	η^1	ω^1
Node 2	τ^2	η^2	ω^2
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
Node n	τ^n	η^n	ω^n

Velocity is determined based on transmission time, inserted in the header of request to route (RTR) packet. The non-synchronization is also solved by the transmission time. When receiving node N replies to sensor node S, it inserts the RTR transmission time in its reply. Once S receives the reply, it subtracts the transmission time from the arrival time to calculate the round trip time. The maximum packet velocity (V) between a pair of nodes is calculated by Equation 1.

$$V = \frac{d(S,N)}{Delay(S,N)} \qquad (1)$$

where $d(S,N)$ is the one-hop distance between source node S and destination node N. In this study, this distance is assumed to be fixed. However, if the sensor node is mobile, the distances can be calculated from the signal strength as shown in [26]. If the velocity is high, the packet has a high probability to arrive before deadline and thus ensure real-time communication.

The link quality of the wireless medium determines the performance of WSN. In designing BIOSARP, the link quality is considered in order to improve the delivery ratio and energy efficiency. It should be noted that the link quality is measured based on PRR to reflect the diverse link qualities within the transmission range. PRR is determined by Equation 2.

$$PRR = \left[1 - \left(\frac{8}{15}\right)\left(\frac{1}{16}\right)\sum_{j=2}^{16}(-1)^j \binom{16}{j} \exp\left(20SNR\left(\frac{1}{j}-1\right)\right)\right]^m \qquad [20]\ (2)$$

SNR is calculated in Equation 3.

$$SNR = P_t - PL(d) - S_r \qquad [20] \qquad (3)$$

where P_t is the transmitted power in dBm and S_r is the receiver's sensitivity in dBm.

In order to track the battery voltage, the precision voltage reference (band gap reference) is monitored to determine the ADC full-scale (ADC_FS) voltage span which corresponds to V_{batt} [27]. The battery voltage is computed in Equation 4.

$$V_{batt} = \frac{V_{ref} * ADC\_FS}{ADC\_Count} \qquad (4)$$

ADC_FS equals 1024 while V_{ref} (internal voltage reference) equals 1.223 volts and ADC_Count is the ADC measurement data at internal voltage reference.

We have added the second heuristic value ω_{ij} in the probability function to consider the link quality of the neighboring nodes while making decision. Jovanovic Raka [28] discuss about heuristic previously. The probabilistic decision rule is expressed mathematically via Equation 5.

$$p_{ij}^k(t) = \frac{[\tau_{ij}(t)]^\alpha . [\eta_{ij}(t)]^\beta . [\omega_{ij}(t)]^\vartheta}{\sum_{h \in j_i^k} [\tau_{ij}(t)]^\alpha . [\eta_{ij}(t)]^\beta . [\omega_{ij}(t)]^\vartheta} \qquad (5)$$

- $p^k_{ij}(t)$ overall desirability for ant k located in city i to choose to move to city j.
- τ_{ij} is a value of pheromone depends on the delay parameter.
- η_{ij} is an heuristic evaluation of edge (i,j).
- ω_{ij} is the 2nd heuristic evaluation of edge (i,j).
- α, β and □ are three parameters that control the relative weight of pheromone trail and heuristic values.

V / V_m calculate the value of τ_{ij}, V_{batt} / V_{mbatt} calculates the value of η_{ij} and value of ω_{ij} is obtained by PRR. Where V_m is the maximum velocity of the RF signal that is equal to the speed of light. V_{mbatt} is the maximum battery voltage for sensor nodes and is equal to 3.6 volts [25]. The determination of

PRR, battery voltage (V_{batt}) and packet velocity (V) is elaborated in the following sections.

While data forwarding, the node first calls the DA. DA selects the optimal node based on the pheromone value stored in neighbour table. DA moves hop by hop on the base of pheromone values for neighbouring nodes until the destination as shown in Figure 2. At the time of selection, if DA could not find the entry, it invokes SA as given in Figure 2. The SA search for new nodes and calculates their pheromone value through the probabilistic rule 5.

Conversely, if flag is 1 and pheromone value is between 0 to 1, the data is forwarded to the node having optimal pheromone value. Otherwise, the source node checks forwarding metrics and compute the new pheromone value by Equation 5. The calculated pheromone value is stored in the neighbour table against the particular node entry. The process of calculation finish when the best pheromone value is obtained to perform optimal forwarding.

Every ant agent is generated with a sequence ID and also is set with maximum time to live (TTL). By the help of assigning sequence ID, sensor node will not accept reappearance of the same ant agent to avoid routing cycles. If an ant agent does not reach its destination before a given TTL value, the ant is destroyed.

Energy management is evolved to maintain the energy consumption of every sensor node in WSN. Power level maintenance helps WSN to extend its life time as long as possible. In order to achieve high gains in the overall performance of WSN, cross-layer interaction is used in the design of our routing mechanism.

3.1 Cross-Layer Design

The concept of cross-layer design is about sharing of information among two or more layers for adaptation purposes and to increase the inter-layer interactions [24, 29, 30]. The proposed system uses interaction between the physical layer and the network layer in order to select the best next node as shown in Figure 7.

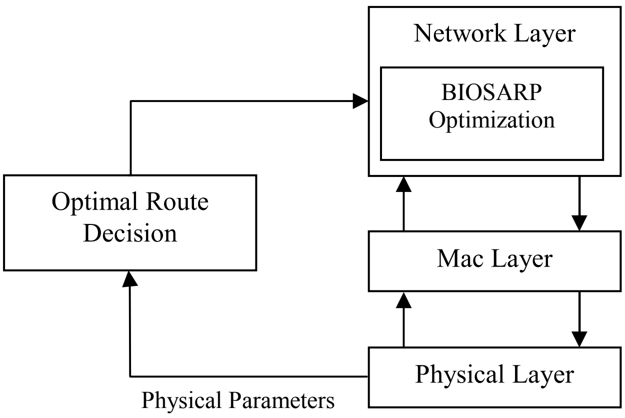

Fig. 7 Cross layer architecture

The process at the network layer comes up with the optimal decision based on the physical parameters, which are then translated as forwarding metrics. The acquired physical parameters are signal strength, remaining power and timestamp. The forwarding metrics are used to get an optimal decision. The forwarding mechanism is requested only during neighbor discovery and network initialization phase.

4 Simulation

The scenario was simulated using network simulator 2 (NS2) [31] based on the network topology. 121 wireless sensor nodes were deployed onto 100 x 100 m^2 grid as shown in Figure 8. For the bio-inspired routing algorithm implementation under NS2, the program is written in C++ and OTcl programming language.

The network model for BIOSARP has been developed based on Table 2. The network model used in this research conforms to IEEE 802.15.4 MAC and physical layers. Many-to-one traffic pattern is used which is common in WSN applications. This traffic is typical between multiple source nodes and a base station. In all simulations, each node updates its neighbour table every 180s. The neighbourhood management of the BIOSARP protocol is designed to maintain those nodes that have good progress towards the destination.

During the animation produced by nam we can examine the output of network. We assume the traffic used is constant bit rate (CBR) with User Datagram Protocol (UDP). Thus, there is no retransmission for the data packet.

The CBR traffic is produced from node 120, 110, 100 and 90 to the sink node 0. All nodes have neighboring tables which contains the information about the neighboring nodes. Depending on information pheromone value is calculated via probabilistic rule. The parameter weights α, β and □ are adjusted to 0.6. The optimal node is selected based on the pheromone value. A fixed size of one packet is considered in the simulation.

BIOSARP packet header format is shown in Table 3. The sourceaddr and seqno fields are used to fill the source addres and the sequence number of transmitter. The originaddr and originseqno fields are used to fill the original source address and sequence number of the packet. The hopcount fields is used to store the number of hops between the source and the destination. The batt_rem and deadline are used to store remaining power of transmitter and packet deadline respectively. The timestamp filed is used to store the time of packet transmission in order to calculate one hop end-to-end delay.

Table 2. System Properties

Parameters	**Values**
Propagation Model	Shadowing
path loss exponent	2.45
shadowing deviation (dB)	4.0
reference distance (m)	1.0
Parameter	IEEE 802.15.4
phyType	Phy/WirelessPhy/802_15_4
macType	Mac/802_15_4
Operation mode	Non Beacon (unslotted)
Ack	Yes
CSThresh_	1.10765e-11
RXThresh_	1.10765e-11
freq_	2.4e+9
Initial Energy	3.3 Joule
Power transmission	1 mW
Transport layer	UDP
Traffic	CBR

Table 3. BIOSARP packet header format, a) data packet and b) control packet

2bytes	2bytes	2bytes	2bytes	2bytes
source addr	origin addr	seqno	origin seqno	hopcount

2bytes	2bytes	15 bytes
batt_rem	deadline	data

(a)

2bytes	2bytes	2bytes	2bytes
sourceaddr	seqno	Batt_rem	timestamp

(b)

4.1 Performance and Analysis of Simulation

BIOSARP is compared with RTLD routing protocol [25] because RTLD also makes next hop decision based on the same parameters. Also RTLD got the best performance results till yet over WSN. Packet delivery ratio and energy consumption are the metrics used to analyze the performance of BIOSARP and the baseline RTLD.

In simulation the impact of varying network load is accumulated by varying the packet rate. While the end-to-end deadline and simulation time were fixed at 250ms and 100s respectively. The traffic load is varied from 1 to 10.6 packet/s to emulate low data rate in IEEE 802.15.4. The simulation results in Figure 9 show that BIOSARP increases the delivery ratio by 3.5% to 6.5% as the packet rate is varied.

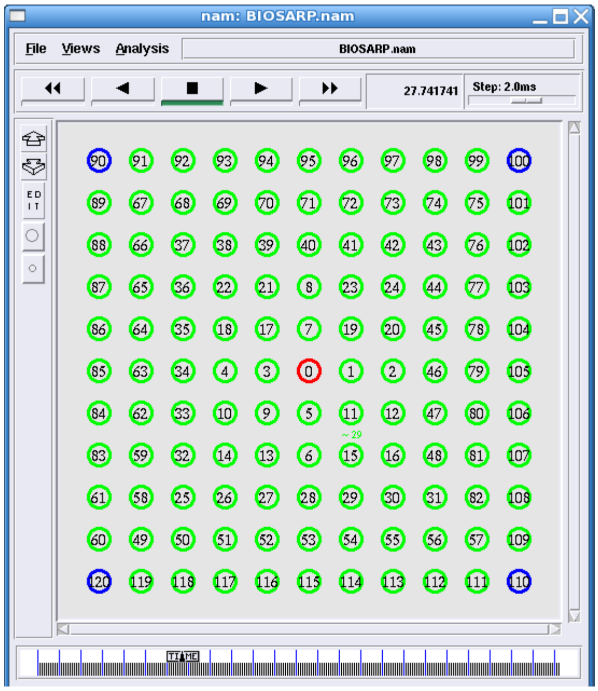

Fig. 8 Graphical Representation

The simulation results of WSNs Lifetime using BIOSARP Routing Protocol is given in Figure 10. The time was varied to analyze the effects of remaining power on the delivery ratio with network lifetime and total power consumption. In this simulation, end-to-end deadline and packet rate are fixed at 250 ms and 10 packets per sec respectively. The simulation results in Figure 10 shows that the BIOSARP consume bit more energy than RTLD because BIOSARP maintain global knowledge over the network.

5 Real Time Experiment

BIOSARP in WSN has been verified through a real time test bed experiment. The test bed performance in term of packet delivery ratio and average packet delay from the source to the destination are analyzed. The results are compared with the simulation output. In this work, 6 Telosb nodes are distributed in a 20m x 15m region as shown in Figure 11. Node 0 is the sink.

5.1 Performance and Analysis of Experiment

The network in the test bed has been configured similar to the network in the simulation. End-to-end deadline and the experiment time were fixed at 250 ms and 100s respectively. The results in Figure 12 show that in the simulation experiences slightly higher delivery ratio about 5% compared to the real test bed implementation. This may be due to the propagation model in the simulation differs from the real test bed environment. In practice, many parameters in the propagation model affect the signal strength including fading, reflection, diffraction and interference.

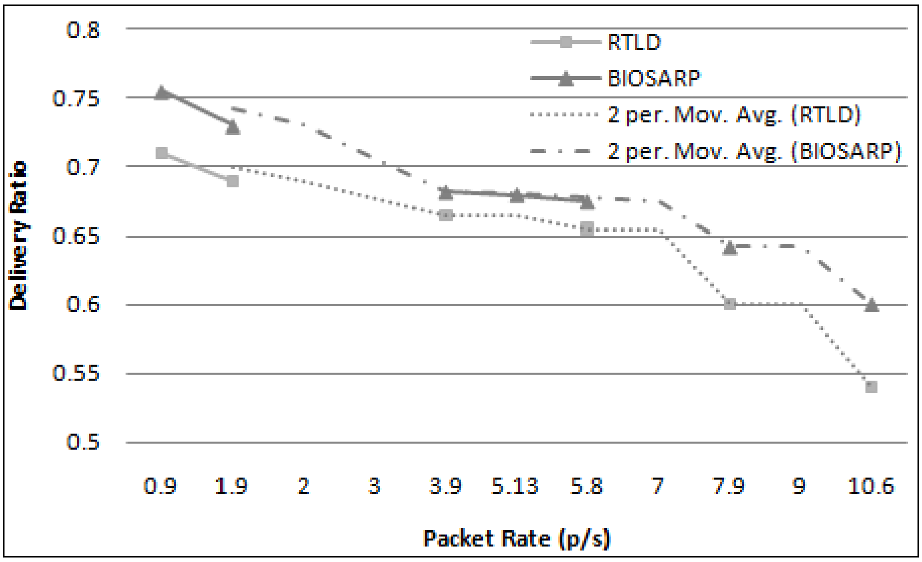

Fig. 9 Delivery Ratio of Different Packet Rate

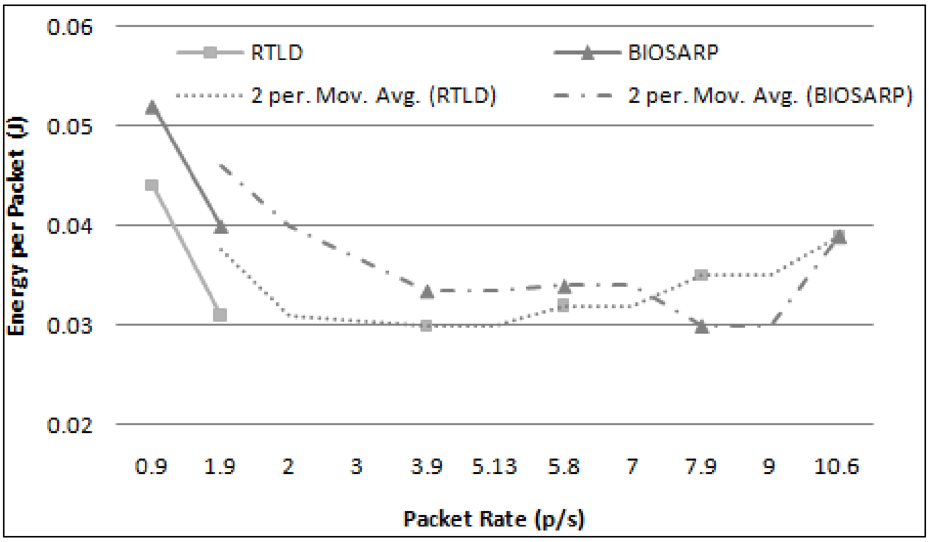

Fig. 10 Energy per Packet (J)

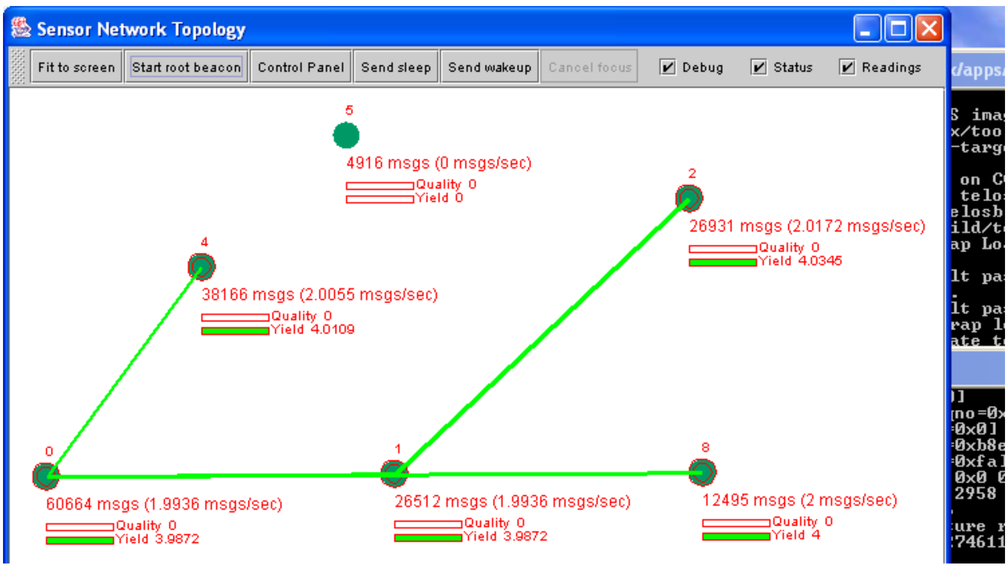

Fig. 11 Network Testbed

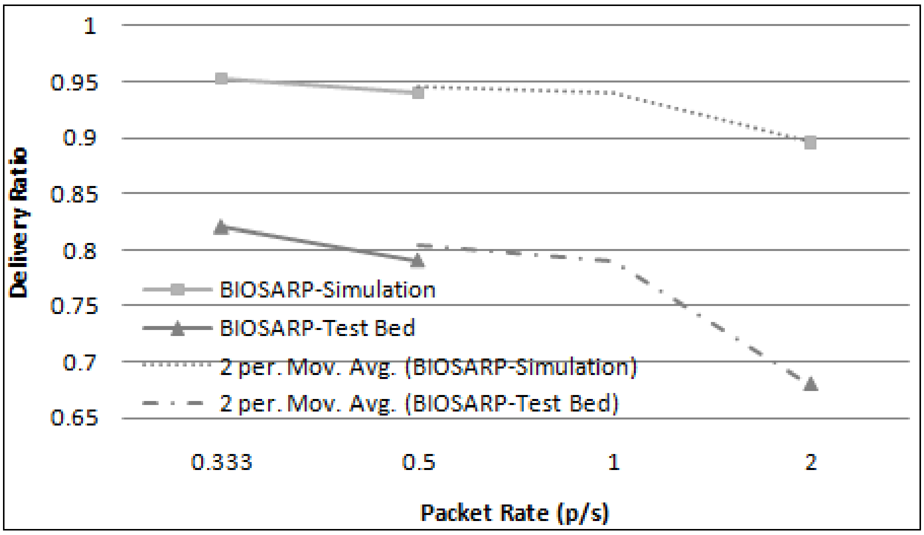

Fig. 12 Delivery ratio of BIOSARP

6 Conclusion

In this manuscript, we have proposed an enhanced ant colony inspired self-optimized routing protocol for WSN. Our specified mechanism is based on link quality, energy and velocity parameters. The adopted cross layer architecture helps WSN in improving the overall data throughput; especially in the case of real time traffic. The cross layer design also assists WSN in better delivery ratio while maintaining energy consumption. The algorithm is also capable of avoiding permanent loops which promotes dead lock in the running networks. Simulation and Experimental results demonstrate the protocol efficiency. Finally, this autonomic routing mechanism will come up with better delivery ratio over WSN. Our immediate future work evolved to enhance our routing mechanism with autonomous security system.

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