Energy Efficient Multipath Ant Colony Based Routing Algorithm for Mobile Adhoc Networks

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ABSTRACT

This paper describes the novel wireless routing protocol made for mobile adhoc networks or wireless sensor networks using bio-inspired technique. Bio-inspired algorithms include the routing capabilities taken from social behaviour of ant colonies, bird flocking, honey bee dancing, etc and promises to be capable of catering to the challenges posed by wireless sensors. Some of the challenges of wireless sensor networks are limited bandwidth, limited battery life, low memory, etc. Energy efficient multipath routing algorithm based on foraging nature of ants is proposed including many meta-heuristic impact factors to provide good robust paths from source to destination in order to overcome the challenges faced by resource constrained sensors. Analysis of individual impact factor is represented which justifies their importance in routing performance. Multi-path routing feature is claimed by showing energy analysis as well as statistical analysis in depth to the readers. Proposed routing algorithm is analyzed by considering various performance metrics such as throughput, delay, packet loss, network lifetime, etc. Finally the comparison is done against AODV routing protocol by considering performance metrics where proposed routing algorithm shows 49% improvement in network lifetime.

1. Introduction

Wireless Sensor Networks (WSN) are nodes which senses and acquires data of particular interest. It is usually constrained with low memory and limited battery life. WSNs are usually deployed over large areas. However depending upon the applications, they can be mobile, interacting with an environment. WSN have wide spectrum of applications which include health care, environmental sensing, traffic control and wild animals tracking. These sensor nodes acquire and send the data towards base station (destination node). Intermediate nodes receiving the data relays further until it reaches the destination node.

1.1. Design Challenges

Though WSNs have variety of application as described above, the quality of communication depends upon the performance of WSNs. When used for routing purposes, WSNs are known for its unpredictable nature due to various design challenges elaborated as follows.

1.1.1. Low Computational and memory requirements

WSNs are having low end computational power and have limited memory. Hence it is vital that a routing algorithm has minimum overhead so that the execution is feasible and effective.

1.1.2. Self-organization

The network topology in WSN is usually dynamic when mobility factor is considered. Apart from this, few new nodes can be added to the network while some older nodes might be dead due to energy depletion or may become nonoperational. Therefore its important that routing protocol should be robust enough to cater to such dynamic and unpredictable events. Self organization property empowers the routing algorithm to let the network function as an autonomous system.

1.1.3. Energy Efficiency

Nodes equipped with small non-rechargeable batteries can communicate for finite period of time. Therefore efficient usage of battery is vital for a routing protocol to have an extended operational lifetime of a network. When diverse paths are used for forwarding the data packets from source to destination, it results in load balancing in which nodes deplete their battery at a comparable rate thereby increasing the lifetime of network.

1.1.4. Scalability

Generally WSN applications consist of utilizing hundreds of nodes which are deployed with short communication ranges leading to high failure rates.

Routing protocols should be able to cater to the aforementioned challenges by being adaptive and robust. Nature provides us countless examples of mobile, independently working agents which seamlessly work together to perform tasks in an efficient manner, for example, foraging behaviour of ants and flight of migratory birds. Algorithms are inspired from nature also known as Swarm Intelligence (SI) [2] are based on collective behavior of birds, social insect colonies and other animal societies for solving different types of communication problems.

Based on foraging behaviour of ants, the proposed routing algorithm is modelled by considering meta heuristic impact factors to cater to the aforementioned challenges. A comparative analysis with AODV routing protocol is presented. The remainder of this paper is given as follows.

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At first general introduction and challenges are given which gives the motivating factors to pursue research in ad-hoc routing followed by the background describing foraging nature of ants. Section 2 discusses about the related work done in the field of ant routing algorithms and other swarm related algorithms. Section 3 describes the working of well known AODV routing protocol. The description of AODV routing protocol is vital as ACO routing algorithm is compared against the AODV in later section. Section 4 briefly describes about traditional ant colony routing algorithm. Section 5 talks about the novel ideas implemented in ant routing algorithm. Section 6 shows the robustness of proposed ant routing algorithm against various test scenarios. Section 7 compares the proposed study against AODV routing protocol. Finally the work is concluded by giving a short summary and an outlook on future work.

1.2. Background

Ant algorithms are special class of SI algorithms [8], consisting of collection of simple agents (ants) which interact locally with the environment. The foraging behavior of ants is the motive behind Ant Colony algorithm. Ants initially wander randomly around their home source searching for food and leave a trail of pheromones on the traversed path which guides them back to their colony. When the food is found, they take it back to the colony and deposit pheromones on the way which guides incoming ants towards food source. Other ants can sense the pheromone concentration and prefer to follow directions with higher concentration. Since shorter paths can be traversed faster, they become more favourable compared to the less optimal routes in terms of pheromone concentration. Additionally, pheromones have evaporation property, so ants are less likely to follow an older path which makes them search for newer paths simultaneously. In a case where an obstacle gets in their way, ants again initiate the route discovery process by randomly selecting the next hop until they find the destination via paths with relatively higher concentration of pheromone.

2. Literature Review

AntNet proposed by Di Caro and Dorigo [6] is a routing technique which is applied for best-effort IP networks. Optimization of the network performance is its main aim according to the principles of Ant Colony Optimization. AntNet is based on a greedy stochastic policy, where each node maintains a routing table and an additional table containing statistics about the traffic distribution over the network. The routing table maintains routing entries for each destination and for each next hop a measure of the goodness of using the next hop to forward data packets to destination. These goodness measures, called pheromone variables, are normalized on the stochastic policy. Forward ants and backward ants are used in this algorithm to update the routing table. The forward ants use heuristic based on the routing table to move between a pair of given nodes and are used to collect information about the traffic distribution over the network. The backward ant stochastically follows the path of forward ants in reverse direction towards source node which is their destination. At each node, the backward ant updates the routing table and the additional table which contains traffic statistics of the network.

Butterfly Optimization Algorithm (BOA) [1] for node localization in WSN proposed by Arora et al, discusses determining the position of nodes using nature inspired metaheuristic approach, i.e. butterfly optimization algorithm. Position of sensor nodes in a network are determined with the help of those nodes whose position is known which are anchor nodes by using various measurements such as time of arrival, angle of arrival, etc. BOA is based on foraging behavior of butterflies which can locate the nectar source with the help of receptors. Butterfly usually gets attracted to those counterparts who has higher concentration of fragrance on their bodies. This phase is known as global phase. When butterfly is not able to sense fragrance greater than its own, it then takes random walk mobility approach, known as localized phase. Searching for the food takes place on both global and local scales. Various factors such as rain, wind, etc. impacts the probability of food searching activities for the butterflies. This probability decides when to switch between global search and local search.

The energy-efficient ant-based routing algorithm (EEABR) is a routing protocol for WSNs and extends AntNet routing algorithm proposed by Tiago Camilo et. al., [3]. In EEABR, memory requirements as well as the overall energy consumption of the original AntNet algorithm is minimized. The ants possess information of only last two visited nodes because it takes into account the size of ant packet to update pheromone trail. In the typical ant-based algorithm, each ant carries the information of all the visited nodes. Then, in a network consisting of very large number of sensor nodes, the size of information would cause considerable energy to send ants throughout the network. In EEABR, each node keeps the information of the received and sent ants in its memory. Each memory record contains the previous node, the forward node, the ant identification, and a timeout value. The transmission probability considers the artificial pheromone value and the remaining energy of the possible next hop.

WSN localization proposed by Strumberger et al, presents hybridized moth search algorithm approach [22] for node localization. Moth search algorithm has been inspired by certain characteristics of moths such as photoaxis, levy flights. Photoaxis is characteristics of moths particularly inhibited by lower fitness levels where when far away from light source, they tend to fly around the light source in line (intensification). Levy flights is used in those algorithms that require optimization. Levy flights are type of random walk (exploration) that are modeled in the form of power law. The moths that are nearer to best moth in the context of light source will fly around the best moth in the form of Levy flights and particularly have high fitness levels. Moth search algorithm is further improvised by including Artificial bee colony approach. In this if moths following photoaxis phenomenon don't converge in certain number of attempts, they are then replaced with randomly generated individual.

Ladder Diffusion Algorithm proposed by Ho et al. [14] addresses the issues of energy consumption and routing problem in WSNs. The algorithm reduces the energy consumption and processing time to build the routing table and avoid the looping of route. In this algorithm, the sink node broadcasts the ladder creating packet with the grade value of one. The grade value of one means that the sensor node receiving this packet will need only one hop to transmit the data to the sink node. Then relay sensor nodes increments the grade value of ladder creating packet and broadcast the modified ladder-creating packet. A grade value of two means that the sensor node receiving this ladder-creating packet sends data to the sink node requires two hop counts. And this step repeats until all the sensor nodes get the ladder-creating packet. The ladder diffusion algorithm makes sure that the direction of data transfer always occurs from a high grade value to a low grade value, which means each relay is forwarded to the sink node since each sensor node records the grade value of relay nodes in the ladder table. The path decision is based on the estimated energy consumption of path and the pheromone value present in the routing table.

WSN localization based on Cuckoo search algorithm [12] proposed by Goyal et al, presents novel cuckoo search algorithm to localize the sensor nodes with an unknown position. Some species of cuckoos lay eggs in the nest of other host birds such as crows. If the host bird recognizes that the eggs belong to an intruder (cuckoo), they either throw away the alien eggs or abandon the nest and builds new nest somewhere. Some cuckoo species have evolved in such a way that they specialize in producing eggs which have patterns and colors similar to that of host bird which is hard to distinguish. This reduces the chance of their eggs being abandoned or destroyed. The algorithm is as follows. Select cuckoo randomly based on Levy flights approach. After evaluating the fitness, a nest is chosen randomly. If the cuckoo's fitness is less than that of nest, the nest is replaced. Otherwise, the nest is chosen as the solution where fraction of worst nests are abandoned and the solution is built around it. The solutions are then ranked and the best one is chosen as a destination.

Energy-Aware Ant Routing Algorithm (EARA) in Wireless Multi-Hop Networks proposed by Michael Frey et. al., [11] provides new mechanisms for estimating the quality of a path and energy information dissemination thus enabling to prolong the network lifetime. The network lifetime is the time span a network can fulfill its service or sometimes it is also defined as the time at which the first node in the network is dead. Traditional Ant Routing Algorithm considers only the pheromone value in its probabilistic routing decision process. Although this approach favours optimal paths over non-optimal paths, but it is not favourable for energy constrained networks. EARA expands the ant routing algorithm with an energy heuristic for determining the nodes residual energy for estimating a paths energy. Since the residual energy of a node changes over time, periodic Energy Ants are released occasionally for updating the energy values in the nodes routing table. Periodic Energy Ants are not sent regularly as it can be a costly operation in terms of consumed energy.

Ant Colony and Load Balancing Optimizations for AODV Routing Protocol proposed by Ahmed M. Abd Elmoniem et al., [9] discusses about improving the AODV routing protocol by taking the Ant Colony Optimization into consideration. Forward ant agents are sent as a part of route establishment request to find the path to destination. This route establishment phase is very much similar to Route Request (RREQ) phase of AODV routing protocol except for the fact that if the route to destination does not exist and there exist no neighbour, then the ant is broadcasted to all neighbors. Otherwise, if the active neighbour exists with highest pheromone, the forward ant is sent to that neighbour. In case of destination node receiving forward ant, backward ant is sent to the source node with a route to destination which comes under the part of Route establishment reply phase. The pheromone update policy is applied on the nodes receiving backward ants. Also it is applied differently depending upon whether the node is an source node or intermediate node or is destination node. Once the source node receives backward ant, the Data transmission phase begins. Each node receiving data packets forwards it to neighbor according to the pheromone values present in the routing table. Neighbor node having greater pheromone receives more data than those having less pheromone. In a way data is distributed along multiple paths which leads to load balancing. If the route does not exist at all, a Route Error (RERR) packet is sent to the source node. If the routing table entry of the destination doesn't exist in source node, it deletes the route and again initiates the route discovery process.

Ant Colony Optimization for Routing and Load-Balancing: Survey and New Directions presented by Kwang Mong Sim et al., [21] provides comparison of the approaches for solving the convergence problem in ACO algorithms. When the network reaches its equilibrium state, the already discovered optimal path is given more preference over other paths by the ants which leads to many problems such as reduction of probability for selecting other paths, network failure, congestion, etc. In order to mitigate this problem, some of the approaches include evaporation, aging, pheromone smoothing and limiting, privileged pheromone laying etc. Evaporation of pheromone is a technique to prevent the ants of following the older or stale paths which makes an ant to simultaneously search for fresh paths. Aging refers to quantity of pheromone deposited by the ant. Older ant will deposit less pheromone compared to its young contemporary since they take more time in reaching destination. Limiting and Smoothing Pheromone refers to limiting the pheromone deposit by placing an upper bound which reduces preference of optimal paths over non-optimal paths In privileged pheromone laying, only certain ants are permitted to deposit extra pheromone. This makes the ant to converge to a solution by taking less time.

Ant-routing-algorithm (ARA) for mobile multi-hop adhoc networks- new features and results explored by Mesut Gunes et al., [13] is based on ant algorithms which makes it efficient and highly adaptive. The routing algorithm consists of three phases. Route Discovery Phase requires use of forward ant (FANT) and backward ant (BANT) control agents. FANT establishes the pheromone trail back to the source node. Similarly BANT establishes pheromone track back to the destination node. Node receiving FANT for the first time creates an entry in its routing table consisting of destination address which is the origin of FANT, next hop which is address of the previous node from which it received FANT and pheromone value which is computed based on the number of hops the FANT took to reach the node. The node forwards the FANT to its neighbors. Once the destination node receives FANT, it sends BANT back to the source node. Once the source nodes receives BANT from the destination node, the path is established and data packets can then be sent which comes under the Route Maintenance Phase. When data packets are relayed to destination by a node, it increases the pheromone value of the routing table entry. The last phase of ARA handles the routing failure caused by the mobility of node which are very common in MANETs. ARA assumes IEEE 802.11 on the MAC layer which enables routing algorithm to recognize the failure of route through a missing acknowledgement on the MAC layer. Node deactivates the link by setting the pheromone value to 0. The node then searches for an alternative link in its routing table. If there exist a route to destination in its routing table, it sends the packet via this path. If there exist multiple en-tries in the routing table, the node will not send any data packets. Instead it informs the source node which has to initiate the route discovery process again.

3. Working of AODV Routing Protocol

Ad hoc On Demand Distance Vector (AODV) routing protocol [18] enables multi hop routing between source and destination node. It is reactive, i.e. on-demand routing protocol where the source node(s) doesn't initiate the route discovery process unless the route to destination is required. On the other hand routing protocols which come under the category of proactive routing continues to maintain routes between source and destination even when the route to destination is not required. AODV routing protocol consists of two phases: i) route discovery and ii) route maintenance.

When a source node wishes to communicate with some destination node, it first seeks for a route in its routing table. If the route exists, then the communication between two starts immediately. If not, then route discovery process is initiated. The route discovery process consists of broadcasting a route request (RREQ) message. If one of the intermediate node receiving RREQ message has a valid route to destination, it replies back with a route reply (RREP) message. Otherwise RREQ message is broadcasted by intermediate nodes until it reaches the destination node. The intermediate node while handling RREQ message increments the hop count value in RREQ packet by one. This accounts for hop count required to reach the source node. Additionally intermediate nodes create a routing table entry which contains address of source node, total number of hops required to reach the source and the next hop's address which is IPV4 address of neighbor node from whom it received the message. Each routing table entry is associated with lifetime, i.e. if the route entry is not used within the lifetime, t will be deleted from routing table. In this way the destination node becomes aware of source node and generates RREP message.

The RREP is unicast to the next hop towards the originator of RREQ message which is indicated by routing table entry for the source node. Intermediate nodes receiving RREP packet increments the hop count field in routing table by one. When RREP is received by source node, the hop count field represents the total distance, in terms of hops, to reach destination node. This completes the route discovery phase.

The second phase of the protocol is route maintenance. It is performed by source node when the destination or an intermediate node moves. A route error message (RERR) is sent to the source node. Intermediate nodes receiving RERR message update their routing table entry for destination by setting the hop count field to infinity. The source node receiving RERR initiates the route discovery process again.

The flowchart of AODV routing algorithm is given on Figure 1

4. Working of Traditional Ant Colony Routing Algorithm

The basic ACO takes a reactive probabilistic approach of finding good robust paths between source and destination. At regular intervals, a foraging ant is launched with a mission to find a path to destination. This establishes backward pheromone trail from destination to source. When an intermediate node receives a foraging ant for the first time, it creates an entry in its routing table. The entry consists of destination address which is the source address of the foraging ant, next hop which implies the node from which it received the packet, and pheromone value. The intermediate node increments the pheromone value by a constant amount whenever it receives a corresponding packet.

The foraging ant probabilistically selects the next hop to reach destination using the formula given below [7].

$$P_{n,d} = \frac{(\tau_{n,d})^{\beta}}{\sum_{j \epsilon N}(\tau_{j,d})^{\beta}} \tag{1}$$

where $P_{n,d}$ is a probability to select neighbor n as a next hop towards destination d, $\tau_{n,d}$ is a pheromone value at neighbor n to reach destination d, N is the set of neighbors and β is a pheromone coefficient constant.

Duplicate foraging ants are then removed by identifying their unique sequence ID and once a foraging ant reaches its destination, it initiates unicast relaying of backward ants until it reaches the source node. The backward ant establishes

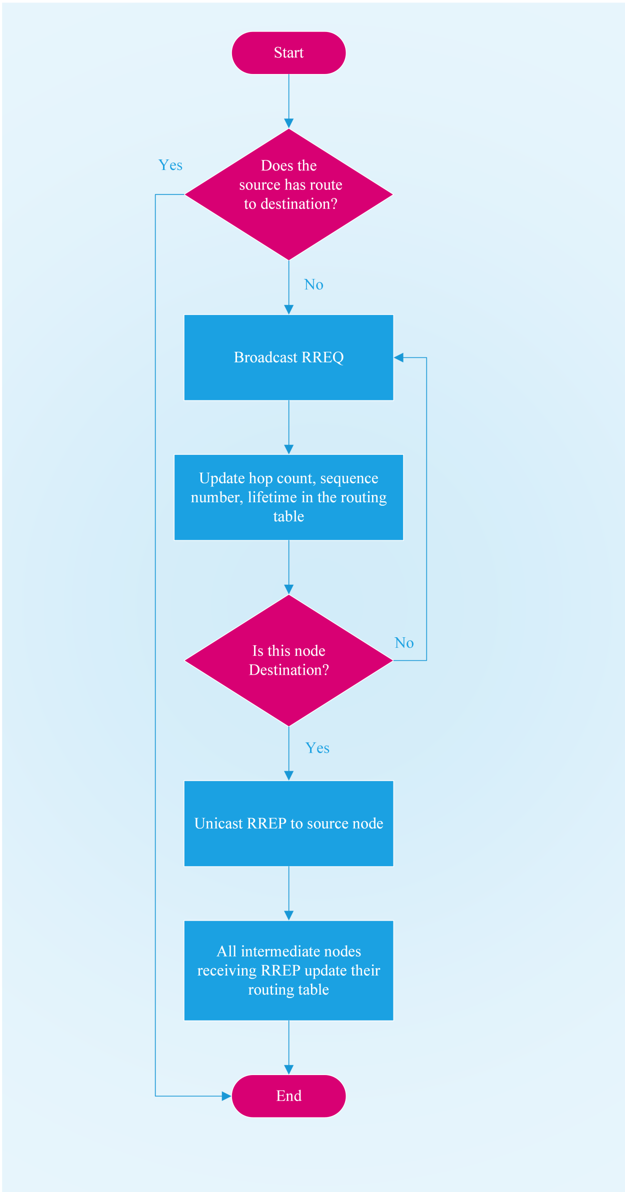

Figure 1: Flowchart of AODV routing protocol

the pheromone trail from source to destination. After calculating the selection probabilities, the node will forward the data packets to the neighbor node. The data packet is sent to the selected relayed node and is further relayed towards the destination node. The selected relay nodes increments their pheromone value by a specific amount. Like their natural counterpart, artificial pheromones decay over time. The evaporation process provides a negative feedback in the system which helps ant avoid the stale paths in the network. The procedure finishes once the data packet reaches the destination node.

Nodes maintain the neighbor entity in its neighbor table by sending Hello Packet periodically to each other. If a node doesn't receive Hello packet from a neighbor for a certain period of time, it then deletes the neighbor information from its neighbor table.

5. Proposed Idea

The traditional ant colony routing algorithm as discussed in Section 4 has some drawbacks. It considers pheromone as the only factor during the routing decisions. Thus the path which has relatively higher concentration of pheromone is likely to be more favorable among the other paths during packet forwarding decisions. As a result, resources of nodes along pheromone optimal path will be consumed more compared to resources along non-favourable paths.

In this section, many other impact factors along with pheromone are considered in the proposed routing algorithm which makes load balancing of the network even more even and distributed in order to get more multiple paths between source and destination pair. This makes the proposed routing algorithm to optimize the usage of the resources.

RSSI: In WSN, sensor nodes are aware of the proximity of their neighbors through RSSI. If the scenario is considered where the topology of network is sparse such that nodes barely come under the transmission range of neighboring nodes, then the nodes during packet reception phase will receive packets with very low RSSI as the power of received signal decreases with distance from the transmitting node. As a result the chances of packet drops are very high which will result in increase in packet re-transmissions. Whereas if dense topology network is taken into consideration, then the nodes will receive packets with very high value of RSSI due to close vicinity with each other. This will result in higher number of hops required for a packet to reach the destination. Higher number of hops thereby increases latency in the network which causes difficulty in delivering data packets resulting in packet losses. This too will result in increase in unnecessary packet re-transmission.

Therefore, it is understood that extreme values of RSSI is not appreciated for our proposed system. With the logic of RSSI explained above, it is vital that the goodness of RSSI closely follows the Gaussian distribution [20] as shown in the Figure 2.

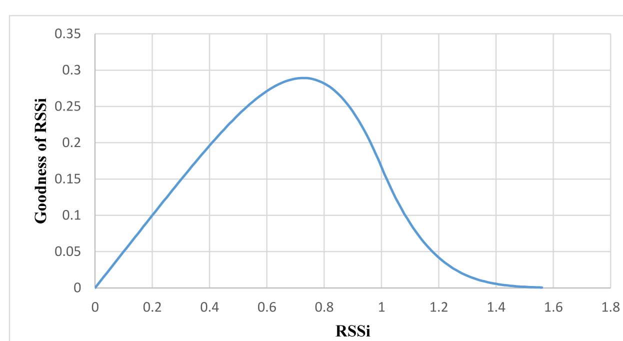

Figure 2: Goodness of RSSI against varying range of RSSI

With reference to [16], if two nodes (source and destination) are placed such that the distance between them is less than the transmission radius R, the total expected hop count from source node to destination node is given by

$$\frac{d}{x}\left[\frac{1}{p(x)[(1-(1-p(x))^u)]}+\frac{u}{[1-(1-p(x))^u)]}\right] \quad (2)$$

where x is the distance between two consecutive nodes. $p(x)$ is the probability of receiving packet and u is a constant and is selected as 1. $p(x)$ is dependent on several measurements such as signal strengths, delay, etc.

By approximating equation 2 and plugging in the value of u, it is simplified by following equation

$$h(x)=\frac{R(1+p(x))}{xp^2(x)}, \quad (3)$$

Taking the inverse of above equation, it is claimed that the Goodness of RSSI [20] is achieved which follows the graph in Figure 2. Hence

$$f(S)=\frac{1}{h(x)}=\frac{xp^2(x)}{R(1+p(x))}, \quad (4)$$

where $f(S)$ is known as Goodness RSSI. Referring to Figure 2, if a node has multiple neighbors, then neighbor nodes which have extreme values of normalized RSSI will be given least preference as a next hop unlike those who have moderate value of RSSI. Each node then maintains a neighbor table where RSSI records are maintained against every neighbors. It is widely known that RSSI fluctuates too often even when static nodes exchange data or hello message [5]. This fluctuation is smoothened by exponential weighted moving average (EWMA).

Residual Energy: If the nodes among the hop optimal path between source and destination are going to be used extensively for data packet transmission, their battery will deplete faster compared to nodes on non-hop optimal paths. This will result in creation of void in the network due to energy depleted nodes which may lead to network partition. Inclusion of residual energy of neighboring nodes [15] in the routing decision will make the network energy aware due to which non-hop optimal paths will also be preferred in relaying of packets. Therefore, having account of multiple paths based on residual energy helps in load balancing which makes the network utilize the residual energy more uniformly. Hence by considering Residual Energy as one of the impact factors, lifetime of the network can be improved.

Hops: The routing tables at each node gets modified by information from the incoming packets. Through the backward learning the node learns the identity of source as well as destination node and also the total hops required to reach them. If a node finds a new path with a shorter hop distance, the hop count information in the routing table is updated to account for newly founded path.

The proposed routing algorithm is an extended version of traditional ant colony based routing algorithm in which the main objective is to maximize the network lifetime by considering various impact factors during routing decisions as discussed above. Traditional ant colony routing algorithm considers the pheromone value alone in its probabilistic routing decision process which is not favorable for energy constrained networks. With additional heuristics discussed above, the extended probabilistic formula is defined as:

$$P_{n,d}=\frac{(\tau_{n,d})^{\alpha}(h_{n,d})^{-\beta}(E_n)^{\delta}(f(S)_n)^{\gamma}}{\sum_{j\epsilon N}(\tau_{j,d})^{\alpha}(h_{j,d})^{-\beta}(E_{j,d})^{\delta}(f(S)_{j,d})^{\gamma}}, \quad (5)$$

where n is the next hop selected by an ant to reach destination d, $\tau_{n,d}$ is a pheromone value from neighbor n to reach destination d. h is the number of hops taken by an ant to reach destination node d. N is the set of neighbors of node. E is the remaining energy in the node, $f(S)$ is the goodness RSSI. α,β,δ and γ are the factors to adjust the relative importance of pheromone concentration, hops, residual energy and goodness RSSI, respectively.

As discussed in Section 2, nodes receiving the ants update the pheromone value in their routing table by depositing a constant value of pheromone in their routing table which acts as a positive feedback. As a result, an impulsive response is observed with regards to pheromone whenever a node receives an ant. Similar to the biological ants, the pheromone value is a function of time which means pheromone value decreases exponentially as the time progresses which makes it volatile.

The flowchart of the proposed ACO routing algorithm is given on Figure 3

6. Simulation Results and Analysis of Ant Colony Routing Algorithm

The Ant Colony routing algorithm is implemented on open source network simulator (ns-3) [17]. Nodes are initially laid out randomly in regular hexagonal structure to account for radio coverage in cellular communication system. This deployment of nodes can be named as hexagonal randomized placement. As shown in Figure 4, the source and destination nodes are placed along the diagonal so that they are far apart. 802.11b is used as underlying WiFi standard (Layer-2). UDP Echo is used as the application layer protocol. Each experiment runs for at least 500 seconds. Various performance metrics have been extracted through the extensive simulations.

Table 1
Simulation Parameters

Simulation specification	Value
Simulation time	500 seconds
Number of nodes	100
Node distribution	randomized
Data packet size	1500 bytes
MAC layer protocol	802.11
Traffic type	UDP
Pheromone coefficient (α)	1
Hop count coefficient (β)	3.2
Energy coefficient (δ)	1.8
RSSI coefficient (γ)	2.3

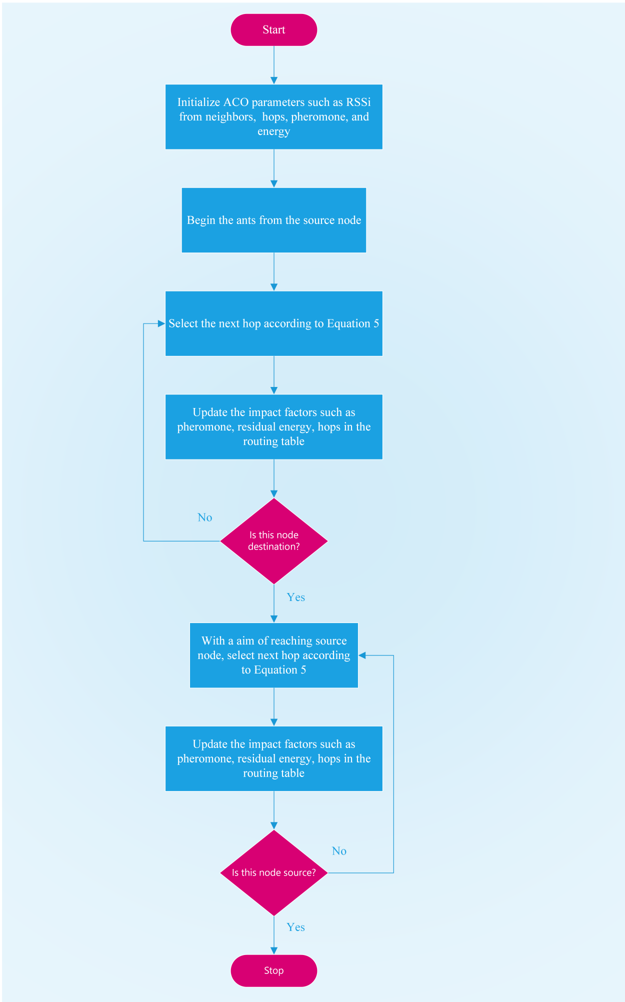

Figure 3: Flowchart of proposed ACO routing algorithm

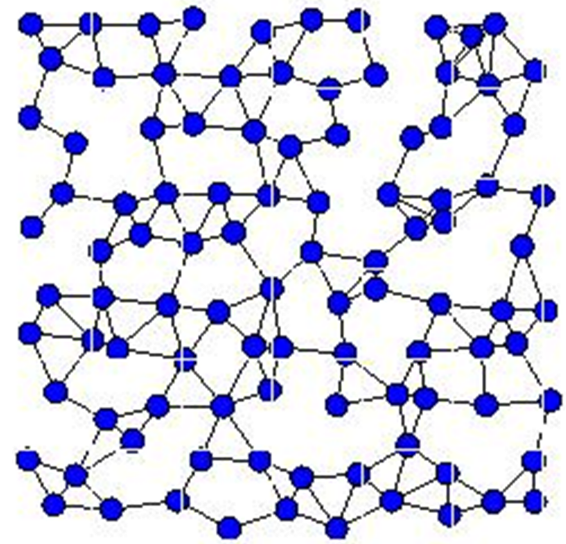

Figure 4: Placement of nodes

6.1. Performance Metrics

6.1.1. Throughput

It is the rate at which the data packets are delivered successfully by the network to destination node from source node, is represented by bits per second. The throughput is affected by various factors such as background traffic/noise, bandwidth of physical medium, processing power, end user medium, etc.

6.1.2. Mean Delay

Mean Delay is the time consumed by the data packet to reach the destination node from source node. Mean delay is calculated by taking the ratio of delay sum to the total number of received packets at the destination node, ignoring any packet drop [4].

6.1.3. Packet Loss

Packet Loss results when one or more data packets fail to reach the destination node due to various reasons such as dropping of packets, error in data transmission, network congestion due to overwhelming loads.

6.1.4. Network Lifetime

It is defined as the time span a network can fulfill its service whereby source node and destination node communicate with each other by exchanging data packets and other control packets. Also in various literature's, it is the time at which the first node in the network becomes dead.

6.1.5. Partition Time

Partition Time is defined as the time beyond which communication between source and destination no longer takes place due to the lack of routing path between a pair of nodes. This happens when the network becomes disconnected due to energy depleted nodes.

6.1.6. Mean Hop Count

Mean Hop Count is the average of hops taken by the data packet to reach the destination node from source node.

6.2. Simulation Results and Analysis

The performance of routing protocol is analyzed under different test scenarios and topologies to account for the robustness.

6.2.1. Background Traffic

The logic of introducing background traffic in simulation is to mimic real life network scenarios where there's a disturbance or white noise along with regular traffic flow. At every regular time interval (50 seconds) a pair of random nodes are chosen as background source and destination nodes which generate background traffic flow. At the end of simulation, there are 10 pairs of nodes which contribute to the background traffic. During the simulation run, each node is able to keep track of the number of packets sent, received and dropped. These results are analyzed at that time when the pair of nodes are chosen randomly for background traffic flow and then the average of resultant is calculated. Hence these attributes are vital for background traffic calculation.

The topology of graph is shown in Figure 5. The minimum average degree of node is 4.94 for the graph to be connected.

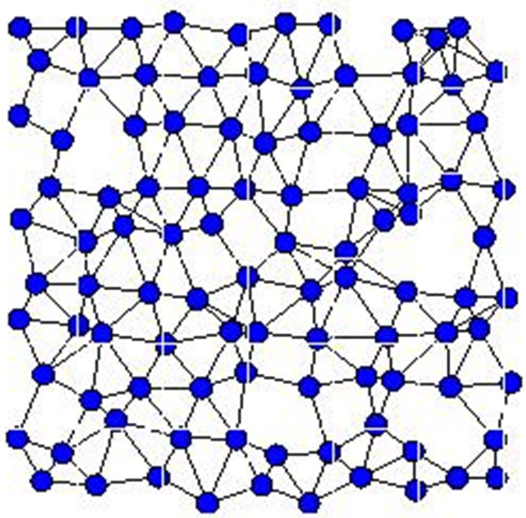

Figure 5: Connectivity of the graph during background traffic

6.2.2. Effect of throughput against background traffic

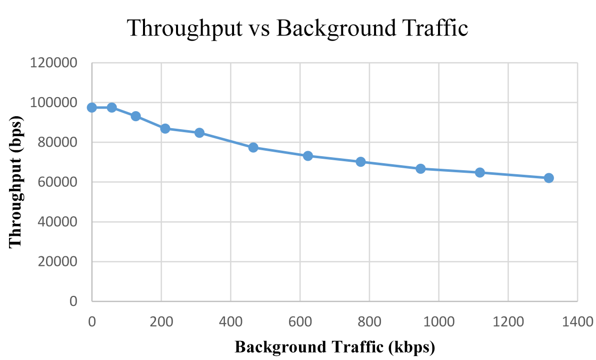

Figure 6: Throughput against background traffic

As per the connectivity shown in Figure 5, probing of traffic flow is done on genuine source and destination nodes throughout the simulation time. As shown in Figure 6, when background traffic overwhelms the network resources, Ant Colony algorithm becomes more sensitive to background traffic as a result, throughput decreases with increase in background traffic.

6.2.3. Effect of delay against background traffic

As per Figure 7, delay increases with increase in background traffic. Since ant colony forms multiple paths with

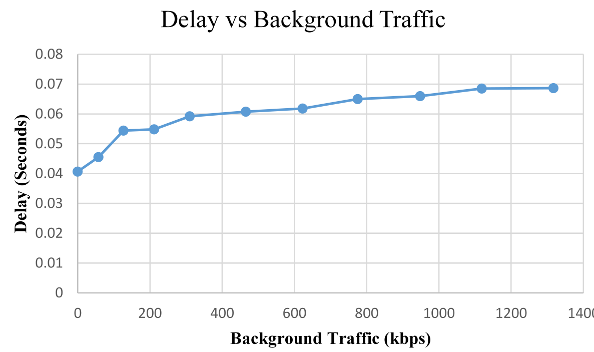

Figure 7: Delay against background traffic

varying hop counts between source and destination pair, these paths are affected by background traffic which brings in the latency in the system.

6.2.4. Effect of Packet loss against background traffic

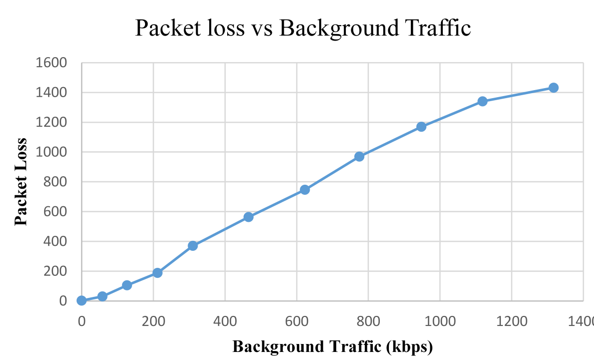

Figure 8: Packet loss against background traffic

Packet loss linearly increases with increase in background traffic. Conditions like packet collision, congestion, overhearing due to background load affects multiple paths between source and destination pair which makes Packet losses more sensitive to background traffic as can be observed on Figure 8.

6.3. Average Degree

The topology and complexity of network varies on the transmission range of nodes. With increase in the transmission range of nodes, the network complexity increases as the node can interact with more number of neighboring nodes leading to interference. In this experiment, the transmission range is varied from 71 meters to 120 meters.

6.3.1. Analysis of Throughput against Average Degree

The Throughput decreases with increase in average degree of the network as shown in the Figure 9. As the transmission range increases, the average degree of network increases, which leads to packet collisions and high interference. It has been observed that when the average degree of

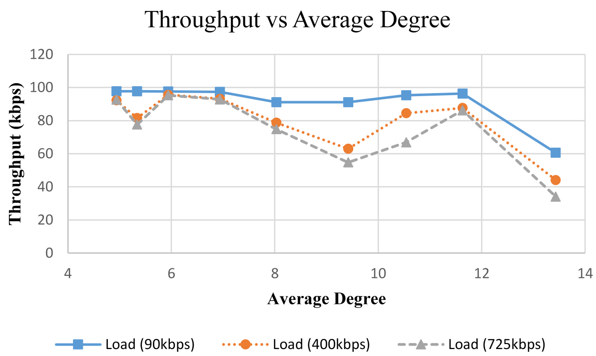

Figure 9: Throughput vs Average Degree

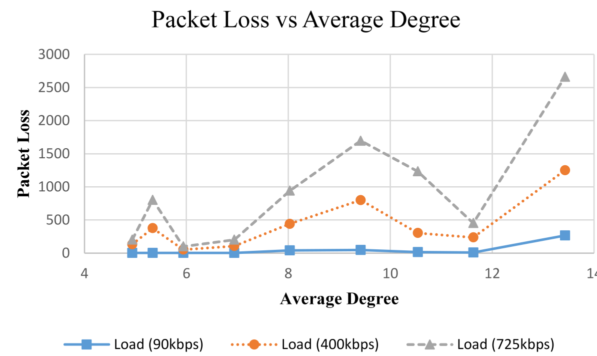

Figure 11: Packet loss vs Average Degree

network is close to 6, the network experiences its best performance as the throughput of network is unaffected by the background load possibly due to best connectivity in the network.

6.3.2. Analysis of Delay against Average Degree

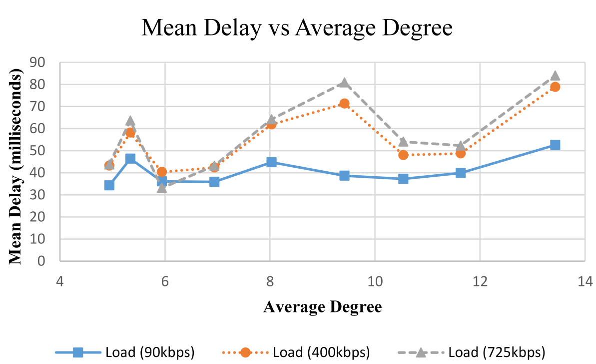

Figure 10: Delay vs Average Degree

It is observed that mean delay is directly proportional to average degree of network. With increase in average degree of node, the node density becomes higher, which means a node can access more number of neighbors around itself. This leads to increase in overhearing and congestion which is the root cause for increase in delay. However the optimal average degree of network is close to 6 as the delay of network is hardly affected.

6.3.3. Analysis of Packet Loss against Average Degree

Packet loss is expected to increase with increase in node density due to overhearing and congestion. The packet loss is found to be the least when the average degree of network is around 6 as it offers best connectivity.

6.4. Randomness Property of Ant Colony Routing Algorithm in terms of Hop Count

This section claims about the random hop count property of the proposed routing algorithm by showing the 95% confidence interval. Against every minimum path between source and destination node, the mean hop between them is calculated along with the confidence interval that gives a range of hop count values with 95% surety.

The Figure 12 shows the confidence interval of hop counts between the source and destination node which can be understood in following way.

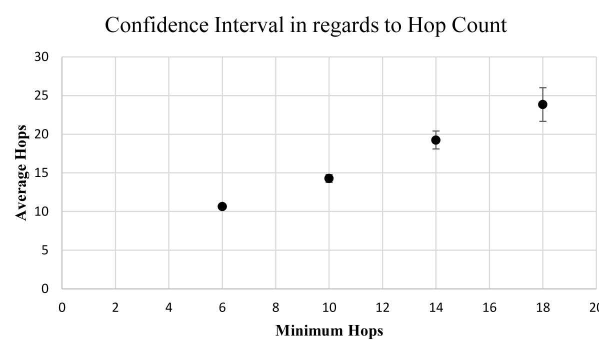

Figure 12: Confidence interval in terms of hop count

Suppose when the source node and destination node are placed in such a way that the minimum number of hops between them, let's say is 18 as shown in Figure 12, there's 95% chance that the packets received by the destination node will have hop count in the range from 22 to 27 hops. This means that even though when the optimal hop path is found, the algorithm considers other non optimal hop paths due to randomness behaviour in packet forwarding.

The Figure 13 shows the hop count distribution for every minimum hops shown in Figure 12.

6.5. Importance of Impact factors in Ant Colony Algorithm

This section discusses about the need of individual impact factors taken into the consideration as described in section 5

6.5.1. RSSI as an impact factor

Using RSSI is a well known technique to measure distance between source and receiver. The distance is estimated

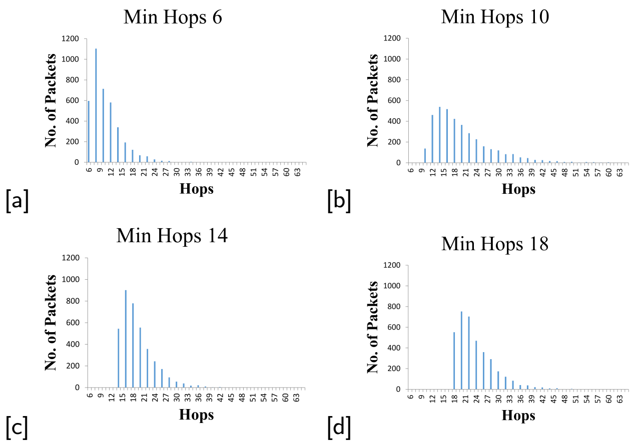

Figure 13: (a) Hop count distribution for 6 minimum hops (b) Hop count distribution for 10 minimum hops (c) Hop count distribution for 14 minimum hops (d) Hop count distribution for 18 minimum hops

by using the strength of received wireless signal. The relationship between RSSI and distance is inversely proportional. Low values of RSSI cause more number of packet losses which in turn makes failure of transmissions of packets. The motive behind this analysis is to find the total number of failed transmission of data packet by varying the weightage of RSSI coefficient. Each node gathers this data from MAC (L-2) layer.

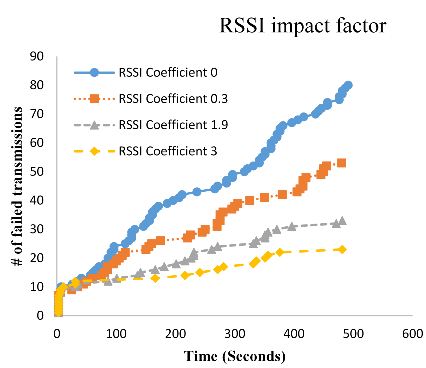

Figure 14: Importance of RSSI Coefficient factor

The Figure 14 shows how the failed transmission of packets can be controlled with RSSI impact factor. RSSI Coefficient 0 signifies there's no consideration of RSSI in the routing algorithm due to which maximum failure of packet transmissions are observed. When the RSSI is taken into consideration by increasing the weightage of RSSI coefficient, the number of failed transmissions of data packets drops down.

6.5.2. *Hop Count as an impact factor*

Hop Count information is used by the nodes to learn about the how far they are from source and destination. This knowledge gathered from this data helps to reduce the end-to-end delay in routing as much as possible.

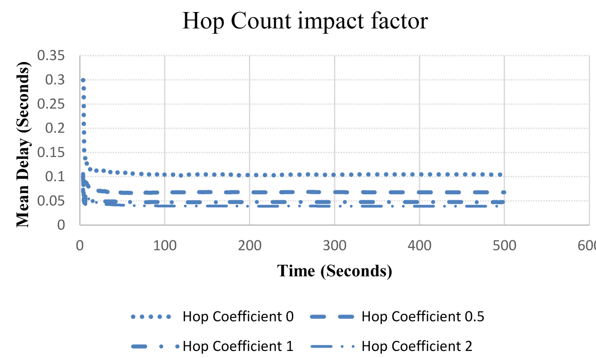

Figure 15: Importance of Hop Count factor

With reference to the Figure 15, highest delay is observed when hop count factor is turned off (hop coefficient 0) as the routing protocol has no knowledge about the source and destination. When the preference to hop count factor is increased by changing the hop count coefficient, the nodes are aware of source and destination in terms of hop counts and the reduction in end-to-end delay is expected. Overall 60% reduction in delay is observed.

6.5.3. *Residual Energy as an impact factor*

The inclusion of residual energy as an impact factor in Layer 3 (IP layer) routing makes the protocol energy aware as the routing decision considers the residual energy among neighboring nodes while forwarding the data packet . If this impact factor is excluded from routing, the reduction in network lifetime is expected. With reference to the Figure 16, the time at which the node dies is recorded for every node which gives us the relationship between number of alive node versus time. The source transmits data at every second. When the energy impact factor is not considered (Energy Coefficient 0), the first node dies at 459 seconds and the communication link breakage occurs at around 515 seconds, also known as network partition time where source and destination are no longer able to communicate with each other.

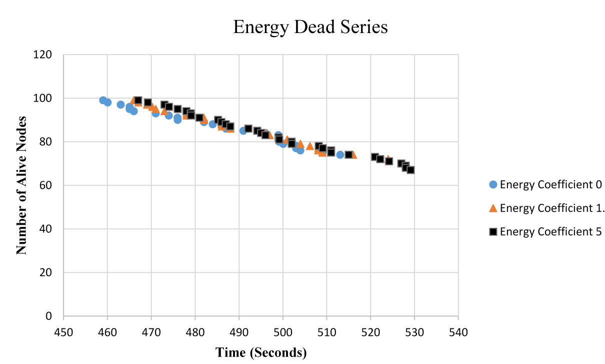

Figure 16: Importance of Energy factor

When slight weightage is given to Energy impact factor (Energy coefficient 1.5), network partition occurs at 524.14 seconds and when energy coefficient is 5, highest energy related performance is observed where the network partition time is around 530 seconds.

Overall 15 seconds of improvement in network partition time is observed when energy impact factor is taken into consideration.

7. Comparative Analysis

This section compares Ant Colony Routing Algorithm against the AODV Protocol. Various test scenarios such as background traffic analysis, varying transmission range, energy analysis, etc. are considered for comparative purposes.

7.1. Background Traffic

7.1.1. Effect of Throughput against Background Traffic

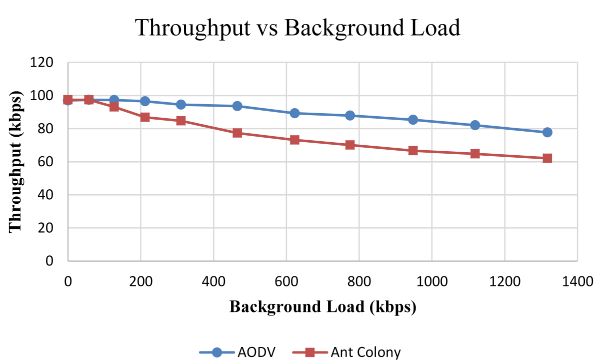

Figure 17: Throughput comparison

It is deduced that Ant Colony is more sensible to background traffic as compared to AODV as it is evident from the throughput trend. Since AODV forms path between source and destination pair with least number of hops unlike Ant Colony, it suffers less packet loss comparatively which makes the throughput performance better than Ant Colony.

7.1.2. Effect of Delay against Background Traffic

AODV experiences lesser delay as compared to Ant Colony protocol. The reason is that AODV forms the shortest path between source and destination. As a result, even though delay in AODV increases with background traffic, its going to be lesser than that of Ant Colony. Ant Colony Algorithm is not designed for routing over the best path between source and destination which makes the performance of AODV better than Ant Colony in terms of delay.

7.1.3. Effect of Packet loss against Background Traffic

Ant Colony suffers more packet loss against increase in background traffic when compared to AODV. Along with optimal hop path between source and destination, Ant Colony constructs multiple paths with higher hop counts. Therefore the probability of packet losses along higher hop count paths

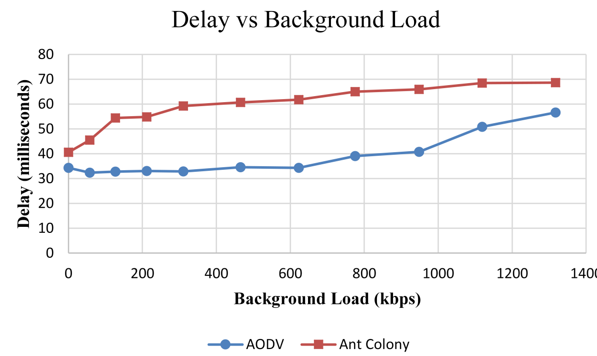

Figure 18: Mean Delay Comparison

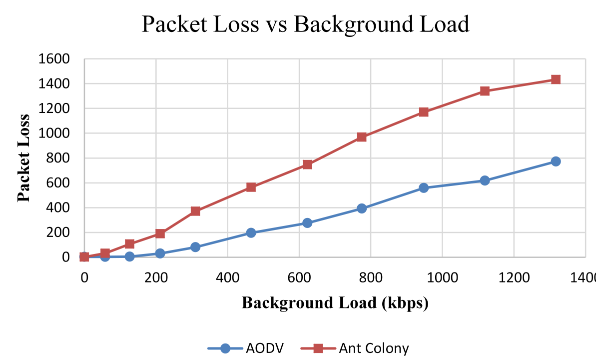

Figure 19: Packet loss comparison

is more than AODV which only constructs hop optimal path. This makes Ant Colony more prone to packet losses.

7.2. Average Degree

As described in previous section 6.3, the topology is made dense by changing the transmission range of all the nodes and the performance metrics are measured.

7.2.1. Throughput effect against average degree

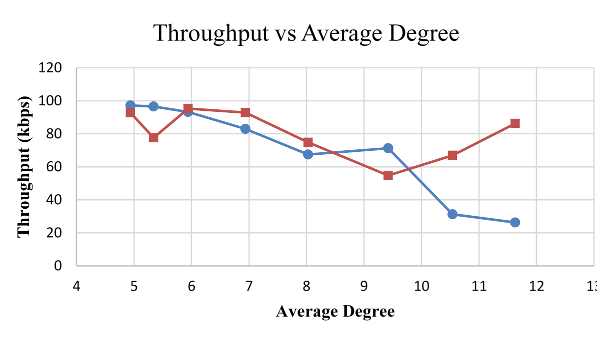

Figure 20: Throughput comparison against Average Degree

By including the background load in the system, the throughput is measured against varying transmission range and then the following observations are made. Ant Colony attains maximum throughput at average degree of 6 whereas AODV has its maximum throughput at average degree of 4.94. During increase in transmission range, AODV experiences more packet loss as shown in Figure 21 due to network congestion which makes the throughput performance lower than that of Ant Colony.

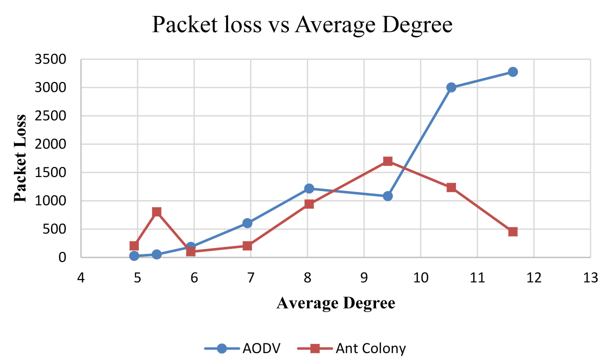

Figure 21: Packet loss against average degree

7.2.2. *Effect of Mean Delay against Average Degree*

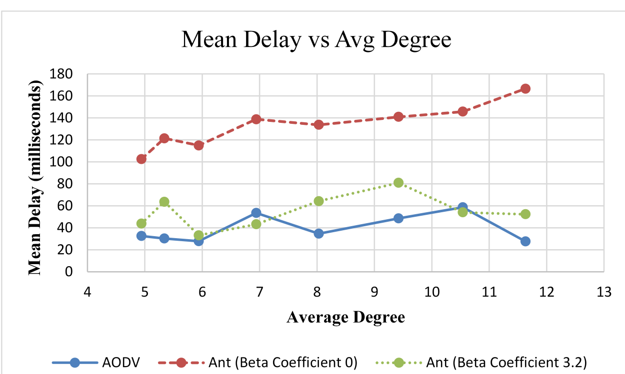

Figure 22: Mean Delay comparison against average degree

AODV outperforms Ant Colony when it comes to delay against increase in transmission range. As AODV forms shortest path between source and destination, with increase in transmission range, packets from source node can reach destination with fewer number of hops making the delay comparatively less. Also in case of Ant Colony, maximum delay is observed that when the hop count impact factor is ignored as the nodes ignore the hop count information in its routing table.

7.3. Energy Comparison

In both AODV and Ant Colony, all nodes are equipped with battery. With reference to data-sheet of FRDM KW41Z [19] micro-controller, the transmitting current has been configured to 6.1 mA, the receiving current is set to 6.8 mA. The micro-controller uses a single coin cell battery [10] which has a idle current capacity of 0.19 mA. The goal in this section is to study the energy analysis and lifetime of the network.

7.3.1. *Energy Depletion Series*

Communication between source and destination takes place at an interval of 2 minutes in order to mimic the wireless sensor network applications. Figure 23 shows the order at which the nodes become energy depleted when two different routing protocols are used.

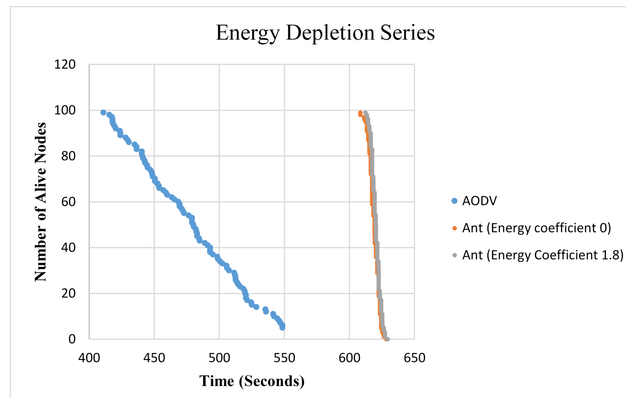

Figure 23: Comparison of dead node series

Figure 23 shows that while using AODV routing protocol, the time at which the first dead node is observed at approximately 411 seconds whereas in Ant Colony, the time at which the first dead node (when δ is 1.8) is observed at approximately 612 seconds. When δ is 0, time at which the first dead node is observed at 608 seconds. Partition time when AODV is used is observed at 549 seconds whereas when using Ant Colony, partition time is 629 seconds. Thus Ant Colony experiences 49% improvement compared to AODV. The inclusion of residual energy as an impact factor in ant colony routing algorithm makes it more better than AODV in terms of energy performance.

7.3.2. *Ranking of Nodes based on Remaining Energy*

In this section, nodes are ranked in decreasing order of their remaining energy against various time stamps and the analysis is compared for both the routing protocols. This helps in understanding of rate of energy consumption in the system over a period of time.

With reference to the Figure 24, the slope of the line gives an idea of energy consumption. At 500 seconds, it is claimed that approximately 30 nodes are energy depleted and at 540 seconds, more than 50 nodes in the topology are dead. More the magnitude of slope, more is the rate of energy consumption. AODV forms single hop-optimal path between source and destination pair and continues to relay the data packets on established path. This makes the node along hop optimal path use more energy in contrast to proposed ant colony routing protocol.

On the other hand, with reference to the Figure 25, it can be inferred that having multi-path as well as load balancing

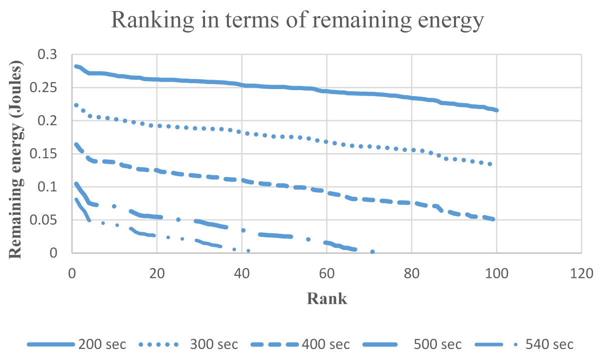

Figure 24: Ranking of Nodes when using AODV routing protocol

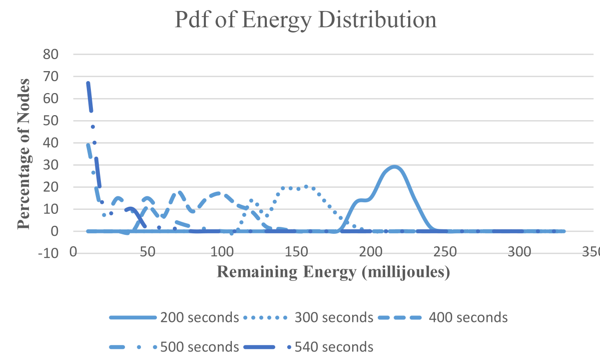

Figure 26: Probability density function of remaining energy when using AODV routing protocol

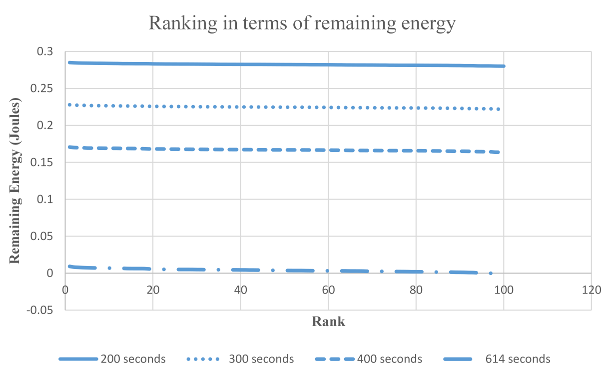

Figure 25: Ranking of Nodes when using Ant Colony routing protocol

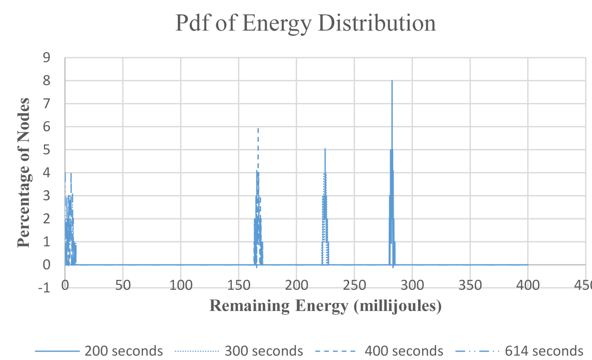

Figure 27: Probability density function of remaining energy when using Ant colony routing protocol

approach during routing process makes energy consumption of nodes relatively equal. This makes the slope of line close to zero in Figure 25. It is claimed that at 614 seconds, three nodes in the topology are energy depleted.

Figures 24 and 25 show that proposed ant colony routing protocol is very much energy efficient compared to AODV routing protocol.

7.3.3. Probability Density Function of Energy Distribution

Through Probability density function, the possibility of outcome is analyzed due to which the background of the routing protocol is gathered. In this section, at different time intervals, the histogram of remaining energy in nodes is shown and is compared for both the routing protocols.

With reference to the Figure 26, it can be seen that for every increase in time stamp, the standard deviation of remaining energy in nodes increases as the curve in the figure becomes more flatter and wider. However in contrast to AODV, the proposed ant colony routing protocol has narrower and taller curve as shown in the Figure 27.

The proposed routing protocol has relatively lower standard deviation of remaining energy which is good for the system. The proposed routing protocol uses remaining energy as one of the impact factors during the routing decision which makes it energy aware. Also the ability to establish multiple paths between source and destination makes the energy distribution of the network relatively uniform due to load balancing. AODV on the other hand follows single hop optimal approach which leads to discrepancy in terms of residual energy of nodes thus making the network have higher standard deviation of remaining energy.

7.3.4. Comparison of standard deviation of residual energy

Starting from time 50 seconds, at regular intervals of 25 seconds, the standard deviation of residual energy for all 100 nodes in the network is calculated and is plotted against time as shown in Figure 28 below.

It is observed that standard deviation of AODV is very high compared to standard deviation of Ant Colony Routing. The reason is in AODV routing, there's only one path between source and destination node. As a result, the nodes along the chosen path are used more compared to the rest of the nodes in the network. This creates a disparity among nodes in terms of residual energy.

Whereas in Ant Colony Routing, there are multiple paths between source and destination. Due to this, most of the nodes are used uniformly during the communication process which makes the standard deviation low due to evenness in

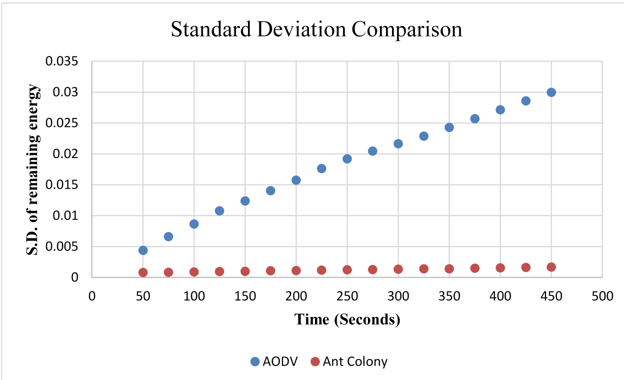

Figure 28: Comparison of Standard Deviation of Residual Energy

remaining energy.

7.3.5. Comparison of Average Remaining Energy

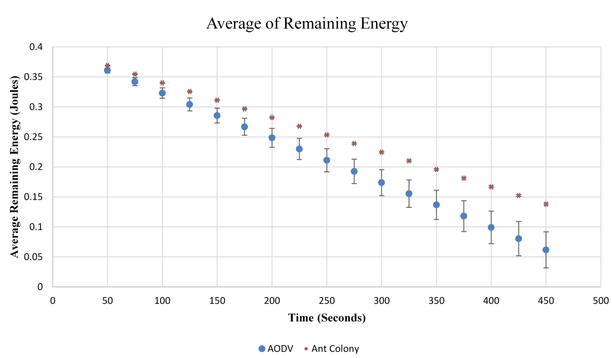

Figure 29: Comparison of average remaining energy

The difference in average remaining energy of ant colony algorithm when compared against AODV is quite high. AODV, being a single path routing algorithm, consumes more energy over a period of time unlike Ant Colony algorithm which constructs multiple paths and has a packet forwarding mechanism which selects the next hop relative to the proportion of impact factors as explained in Section 5. The error bars around the average energy data point shows the standard deviation of residual energy.

7.4. Hop Count Comparison

Hop Count analysis is studied in this section each time by changing the transmission range of nodes. As shown in the Figures 30 and 31, for every time interval, the average of hop counts for first 30 data packets received by destination are calculated and is compared.

It can be claimed from these figures that while using AODV routing protocol, once source establishes route towards destination, it uses the same path no matter how long the communication takes place because it follows hop optimal approach.

With increase in average degree of network it is observed that when AODV protocol is used, there is reduction in av-

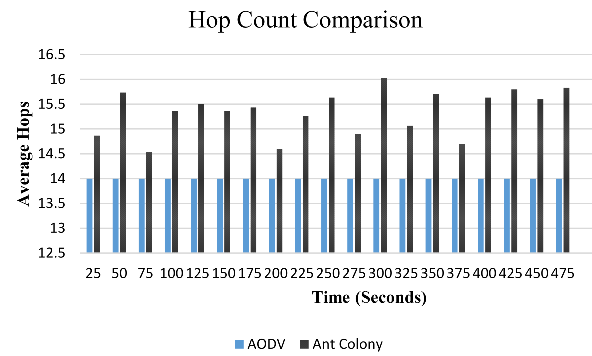

Figure 30: Hop Comparison when Avg degree is 4.94

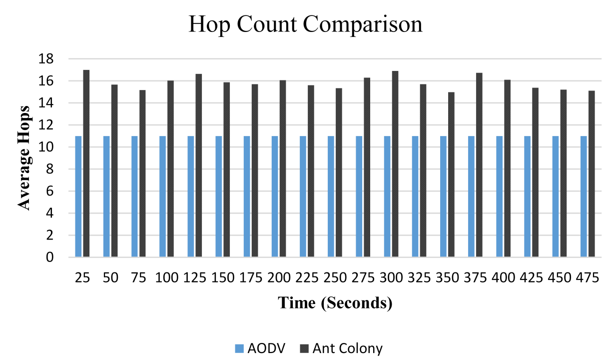

Figure 31: Hop Comparison when Avg degree is 5.94

erage hops of packets from source to destination as AODV uses single shortest path route which makes it hop optimal. Whereas Ant Colony protocol selects the next hop relative to the proportion of impact factors which involves randomness. Hence ant colony protocol is not hop optimal.

8. Conclusion and Future Work

Comprehensive performance analysis of Ant Colony routing algorithm under various load conditions, density of network, etc is carried out in this research. First the challenges faced by sensor networks are described in Section 1.1. The methods to overcome these challenges are elaborated in Section 5 and in Section 6.5 the performance of network is shown by varying the weightage of individual impact factors. Hop distribution and its confidence interval gives the idea of how data packets are forwarded across multiple paths between source and destination.

Performance of Ant Colony routing algorithm was analyzed and compared against AODV routing by considering various performance metrics such as throughput, delay, packet loss, residual energy, etc. In terms of energy analysis, Ant Colony outperforms AODV as the goal for Ant Colony routing is to extend the lifetime of network by constructing multiple paths. There are cases where AODV performs better than Ant Colony routing algorithm since latter involves the decision to forward the packet randomly which doesn't

Table 2
Comparison of the routing protocols

	AODV	*Proposed AntColony*
Route Selection	Reactive	Reactive
Routing Metric	Distance Vector	Metaheuristic impact factors
Loop free	Yes	Yes
Routes maintained in	Routing Table	Routing Table
Multiple routes possible	No	Yes
Load balancing	No	Yes
Periodic broadcast	Yes (Hello messages)	Yes (Hello messages)
Standard deviation of remaining energy	High	Low
Time for the first node to be dead	411 seconds	612 seconds
Throughput performance with increase in background traffic	High	Low
Throughput performance with increase in average degree	Low	High
Delay performance with increase in background traffic	High	Low
Delay performance with increase in average degree	Low	High

always favour the optimal path unlike AODV, which forms shortest paths between source and destination.

It should be noted that the current version of NS-3 simulator doesn't have the module for Ant Colony routing algorithm. Development of this module required good understanding of C/C++ Programming as well as solid networking background.

In future, error handling mechanism can be introduced in IEEE 802.11 MAC layer by including repellent pheromone as one of the impact factors. Ants detour from their established paths and give emergency signals to their peers when they encounter emergency situations such as an obstacle (stone) placed in between the paths, water flowing through the paths, etc. Repellent pheromone can act like a signal to the nodes in which the failed transmission of data packets can be minimized by preventing the forwarding of packet to bad neighboring node.

CRediT authorship contribution statement

Arush Sharma: Experimentation, Research, Programming, Software. **Dongsoo S. Kim:** Data curation, Writing - Original draft preparation, Methodology, Guidance.

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