RESEARCH ARTICLE

SIBER-XLP: Swarm Intelligence Based Efficient Routing Protocol for Wireless Sensor Networks with Improved Pheromone Update Model and Optimal Forwarder Selection Function.

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Manuscript Info	*Abstract*

This paper presents swarm intelligence based Efficient Routing protocol for Wireless Sensor Networks termed as SIBER-XLP which takes into account link quality of the path along with energy, distance to select the best quality path from source to sink for packet forwarding. This work proposes improved Pheromone Update Model and optimal Forwarder Selection Function to select the best next neighbor to forward the packet to the sink node with the sole objective of improving the Network Lifetime by balancing the energy among the nodes in the network to ensure that some nodes along the path do not get depleted fast (resulting in Network disconnections or partitioning) and at the same time selecting good quality links along the path to guarantee that node energy is not wasted due to too frequent retransmissions. The performance evaluation of our proposed approach SIBER-XLP was conducted using NS-2 Simulator considering both Static and Dynamic Scenarios with varying network sizes. Our simulation results indicate that SIBER-XLP performs extremely well in terms of Packet Delivery Ratio, Energy Efficiency and latency.

Introduction:-

The field of wireless sensor networks (WSN) has become a very hot area of research in all its aspects in the continuously and rapidly evolving area of wireless communication. WSN has drawn the special attention of researchers due to the fact that it exhibits more constraints and critical conditions than normal ad hoc networks. Wireless Sensor Networks are usually made up of tiny sensor nodes typically equipped with low-end processors, limited memory, limited non-chargeable battery, limited communication range with small bandwidth links (I.F. Akyildiz et al., 2002). Nodes are deployed either randomly or in a grid-like structure according to the sensing and environmental conditions and requirements. WSN can be employed in a wide spectrum of applications such as Military, Environmental, Health-care and Commercial Applications (I.F. Akyildiz, and M.C. Vuran2010). Despite the different objectives of sensor networks applications, the main function of wireless sensor nodes is to sense and collect information (data) from a target area, process, and transmit the information via a radio transmitter back to a destination station (sink or base station). In order to achieve this task efficiently, an efficient routing protocol is needed to set up paths of communication between the sensor nodes(sources), and the destination station (sink) and the path selection must be such that the lifetime of the network is maximized (K. Akkaya, and M. Younis 2005).

Swarm Intelligence (Bonabeau et al., 1999) has drawn the attention of the researchers due its novelty in addressing the collective behavior of multi-component systems that coordinate using decentralized controls and self-organization. The collective behaviors observed in natural systems such as ant colonies, flocks of birds, and schools of fishes have inspired most of the work carried-out in Swarm Intelligence field. Ant colonies exhibit interesting characteristics which are most desirable in the context of WSN management and control. Ant colonies are able to effectively coordinate themselves to achieve specified global objectives without centralized planning or organizational structure. These cooperative behaviors to accomplish the complex tasks emerge from individual ant's

much simpler behaviors and local rules which they follow by instinct. It is evident that the adaptiveness, flexibility, robustness characteristics exhibited in coordination of their behaviors have made them capable of solving real world problems. On similar lines, WSN can be considered as consisting of simple tiny nodes with limited capabilities working together by creating a cooperative environment to deliver messages, while remaining resilient against changes in its environment. In the literature (M. Saleem, et al., 2010, A. M. Zungeru, et al 2012), several routing protocols with various metrics that use ant colony optimization have been reported for WSN. Ant colony optimization is a meta-heuristic approach inspired by the behavior of real ants seeking the path from their colony to the food source. Real ants explore the possible paths between food source and their colony by depositing pheromones on their return journey to the colony and then follow the shortest path, i.e., the path having the highest pheromone trails from colony to the food source.

In this paper, we present SIBER-XLP, Swarm Intelligence Based Efficient Routing protocol for WSN with Improved Pheromone Update Model and Optimal Forwarder Selection Function. There are two variants of the routing protocols named as SIBER-ELP (with Equal Link Probability) and SIBER-VLP (with Variable Link Probability) designed specifically to suit the environment where the WSN nodes are deployed. We consider two environments where wireless sensor networks are usually deployed – Normal Environment and Harsh Environment. Normal Environment represents WSN in-house deployment for Environment, Health-care and Commercial applications, i.e., top of the buildings, hospitals, Commercial complexes where it is assumed that network nodes have stronger links with equal link probabilities. SIBER-ELP represents the routing protocol for WSN deployed in Normal Environment. Harsh environment represents WSN deployed in the battlefield, forest, disaster prone areas where environment conditions keep changing drastically. In these zones, it is assumed that the network nodes will have links with varying link probabilities. SIBER-VLP represents the routing protocol for WSN deployed in Harsh Environment.

Depending on the environment where they are deployed & the prevailing surrounding environmental & networking conditions, it is noticed that link quality and other related parameters (for example, in heterogeneous WSNs, capabilities of individual nodes are also need to be considered) may vary which are not taken into account when selecting the next forwarder by various ant colony based routing algorithms for WSN reported in the literature. Taking these into account, our approach suggests an improved Forwarder Selection Function to select the best next neighbor to forward the packet to the sink node. It is also observed that The Pheromone Update Model varies from one algorithm to another as the parameters used in the computation of the amount of pheromone concentration to be placed on the path traversed by the backward ant differ. Further, it is found that the amount of pheromone computed to be placed on the path during return journey is not proper to reflect that path as the optimal during the simulation period. Strongest path should have largest amount of pheromone whereas weakest path should have least amount of pheromone or almost zero. Among the competing stronger paths for selection, the variations in pheromone concentration should be such that always strongest path (i.e., optimal) is selected. Keeping these in mind, pheromone update model has been designed considering the parameters the forward ant has collected during its travel from source to the destination, i.e., available average Energy, minimum energy of the nodes along the path, Number of hops (i.e., distance indicating shortest path), and link quality of the path to reinforce a path with enough pheromone to select that path as the best path to reach the sink from the source.

Two variants of the proposed protocol SIBER-ELP & SIBER-VLP are introduced in order to highlight the importance of link quality of the path in harsh environments or in environments where path link quality vary drastically due to environmental conditions which should also be taken into account in order to select the forwarder nodes with good quality links and to reinforce a good quality path with enough pheromone to make it to be selected as the optimal path to reach the sink from source. Our simulation studies clearly show that SIBER-VLP performs better when compared to SIBER-ELP in all respects by taking into consideration actual quality of links along the path in addition to all other metrics whereas SIBER-ELP does not take into account the actual link probabilities, instead assumes that all links have higher equal link probabilities which is only true in normal environments.

Another interesting contribution of this work is the introduction of Threshold Energy, Eth which is associated with every node in the network. Threshold Energy, Eth is defined as the energy at which the node loses its right to participate in packet forwarding and is excluded from the path. Actual Energy of the neighboring node should be greater than the threshold Energy Eth in order to be considered for selection. Moreover, Eth can be used as a tune-able parameter which can be varied depending on the traffic or load and plays an important role in extending the lifetime of the network. In order to save energy and prevent nodes from getting depleted fast, Eth of a node can be

initially raised to a suitable higher percentage of the total energy of that node. This can be applied to all the nodes in the homogeneous network or a group of nodes in a heterogeneous network (with nodes having different capabilities) depending on the traffic & type of processing. This helps in better energy balancing among neighboring nodes of a node of concern. When energy of all the neighboring nodes reach this threshold, then Eth can be lowered to an appropriate value, keeping in view that one of the quality neighbor nodes should always be available for packet forwarding. Or it can be set to the least minimum threshold (Eth_{min}) at which point node will stop participating in forwarding of packets due to energy depletion or disconnection from the network.

The rest of the paper is organized as follows. In Section Related work, we present some of the previous work related to Ant colony based routing approaches for Wireless sensor networks. Section Motivation presents the motivation followed by detailed discussion on our proposed approach SIBER-XLP, Swarm Intelligence Based Efficient Routing protocol for WSN with Improved Pheromone Update Model and Optimal Forwarder Selection Function. The simulation setup, Results, Performance of evaluation of our approaches and discussion are presented in the next section, followed by Concluding remarks.

Related Work:-

In this section, we present some of the previous work related to ant colony based routing approaches for Wireless Sensor Networks.

In the Basic Ant Colony Optimization (ACO) based routing algorithm for WSN (M. Dorigo, and G.A. Di Caro 1998), along with the data traffic, forward ants are launched at regular intervals from source node with the mission to locate the sink node with equal probability by using neighbor nodes with minimum cost along the path from source to sink. At each intermediate node, the forward ants use a greedy stochastic policy to choose the next node to travel. During the travel, the forward ants collect information (such as distance, delay, congestion status and the node identifiers) of the followed path. Once the destination is reached, forward ants die and backward ants are created which take the same path as the forward ants, but in an opposite direction whose mission is now to update the pheromone trail of the path the forward ants used to reach the destination. During this backward travel, local models of the network status and the local routing table of each visited node are modified by the backward ants as a function of the path they followed and of its goodness. Once they have returned to their source node, the backward ants die.

In Energy Efficient Ant Based Routing (EEABR) Protocol (T.C. Camilo et al., 2006), each node knows the best neighbors to send a packet towards the sink. The routing path is optimized in terms of distance and energy of the path. The algorithm uses pheromone distribution in such a way that nodes near the sink have more pheromone when compared to the other nodes. In this work, the memory of the forward ant is reduced by saving only the last two visited nodes. It reduces overhead of exchange messages and conserves energy thereby maximizing the network lifetime. It performs better in terms of energy efficiency, average energy of nodes and the energy of node with minimum energy when compared to basic ant based routing -BABR (T.C. Camilo et al., 2006), and improved ant based routing- IABR (T.C. Camilo et al., 2006). But it does not take into account link quality resulting in excessive delay in packet delivery.

Improved Energy-Efficient Ant-Based Routing Algorithm (IEEABR) proposed in (A. M. Zungeru et al., 2012) is a variant of EEABR with improvements such as initializing the routing tables, assigning priorities to destination nodes, updating the routing tables in case of node or link failure and limiting the release of large number of ants to avoid congestion in the network. The route selection process involves available power of the nodes and the energy consumption of each path as in EEABR. The protocol allows non-optimal paths to be selected for packet transmission, increasing network lifetime and preserving network connectivity. This algorithm shows better performance when the network is dynamic and for higher network density.

Three ant colony based routing algorithms for WSN – SC, FF, FP were proposed by (Y. Zhang, et al., 2004). Sensor Driven and Cost-Aware Ant Routing (SC), as the name implies, assumes that ants use GPS to determine the location of the sink at the beginning of the routing process so that ants can select initially the best direction towards sink to travel and each node maintains cost to the sink from each of its neighbors. The protocol suffers from misleading in path discovery when there is an obstacle or loss of sight of the GPS, which might cause errors in sensing. The SC algorithm is energy efficient but suffers from a low success rate.

Flooded Forward Ant Routing, FF Protocol is a multipath routing protocol which uses broadcast method to route packets to the sink by flooding forward ants to the destination. Flooding can be reduced by allowing only the nodes near the sink to involve in the route selection process. The FF algorithm has shorter time delays; however, the algorithm creates a significant amount of traffic.

Flooded Piggybacked Ant Routing FP Protocol uses constrained flooding of both forward ants and data ants to route data and to discover optimal paths at the same time so as to minimize energy consumption of the network with the data ants carrying the forward list. This will result in good path discovery and packet delivery. Data ants not only pass the data to the destination but also memorize the path which can be used by the backward ants to reinforce the probability on the edges. It outperforms SC & FF with high success rate, but incurs high energy consumption, hence it is not energy efficient.

It has been seen from the detailed analysis of various reported ant colony based routing algorithms for WSN in the literature (M. Saleem, et al., 2010, A. M. Zungeru, et al 2012), most of the ant colony based routing techniques do not consider all the parameters to select the best quality path in terms of energy, distance, link quality and other metrics thereby leading to selection of sub-optimal paths. Based on the parameters used, these approaches can be classified into four categories- I : approaches considering only number of hops (i.e., only distance-shortest path), II : approaches considering only Available Energy in the network, III: approaches considering both Available Energy & number of Hops (i.e., shortest path), IV: approaches considering available Energy, Number of hops (i.e., shortest path), minimum energy. The next section highlights the motivation behind carrying out this work followed by overview of the proposed approach.

Motivation:-
It has been observed from our detailed analysis of various reported ant colony based routing algorithms for WSN that the Forwarder Selection Function to select a node for packet forwarding and Pheromone update model need to be revisited.

- Forwarder Selection Function, i.e., the probability function to select the best next neighbor to forward the packet to the sink node initially uses a constant value of Pheromone or probability value giving equal preference (probability) to every neighbor (forwarder) which is not the case in real situations. Depending on the environment where they are deployed & the prevailing surrounding environmental & networking conditions, it is noticed that link quality and other related parameters (for example, in heterogeneous WSNs, capabilities of individual nodes are also need to be considered) may vary which are not taken into account when selecting the next forwarder. This may result in sub-optimal selection of next forwarder to the sink.
- The Pheromone Update Model varies from one algorithm to another as the parameters used in the computation of the amount of pheromone concentration to be placed on the path traversed by the backward ant differ. Based on the parameters used in the computation of the amount of pheromone concentration, approaches can be classified into four categories.
  - Category I approaches consider only number of hops (i.e., shortest path) to determine the amount of pheromone to be laid on the path of the return travel of the backward ant from sink to source. This will lead to suboptimal solutions as Energy is not taken into account which is the most important component to consider for Energy Efficient Routing design.
  - Category II approaches consider only Available Energy in the network to determine the amount of pheromone to be placed on the traversed path on return journey. Considering only available energy will not lead to an optimal solution. Minimum energy of a node in the path must also be taken into account as it might disrupt (disconnect) the selected path if the energy of the node having minimum energy goes below a specified threshold.
  - Category III approaches consider both Available Energy & number of Hops (i.e., shortest path) in order to determine the concentration of Pheromone Trail to be deposited while traversing from sink to source. But these algorithms do not consider Minimum Energy which is also an important parameter to be considered for selecting the optimal path.
- Category IV approaches consider available Energy, Number of hops (i.e., shortest path), minimum energy to reinforce a path with enough pheromone to select that path as the best path to reach the sink from the source. But it is found that the amount of pheromone computed to be placed on the path during return journey is not proper to reflect that path as the optimal during the simulation period. Strongest path should have largest

amount of pheromone whereas weakest path should have least amount of pheromone or almost zero. Among the competing stronger paths for selection, the variations in pheromone concentration should be such that always strongest path (i.e., optimal) is selected.

In order to take all these issues into account, there is a need to design & implement Swarm Intelligence based (i.e., ant colony based) Efficient Routing Protocol with Modified Pheromone Model and Optimal Forwarder Selection Function which always routes packets through optimal path from source to sink under varying networking and environmental conditions.

Proposed Approach:-
In this section, we present our proposed Model SIBER-XLP, Swarm Intelligence Based Efficient Routing protocol for WSN with Improved Pheromone Update Model and Optimal Forwarder Selection Function.

SIBER-XLP MODEL:-
Our proposed model SIBER-XLP consists of two main components - Optimal Forwarder Selection Function and Improved Pheromone update model which are discussed next.

Forwarder Selection Function:-
Forwarder Selection Function is a probability function that is used at every node along the path from source to sink node in the network to select the best next neighbor to forward the packet to the sink node. The Forwarder Selection Function must always choose an optimal path from source to the sink to forward the packets with the sole objective to improve the Network Lifetime by balancing the energy among the nodes in the network to ensure that some nodes along the path do not get depleted fast (resulting in Network disconnections or partitioning) and at the same time selecting good quality links along the path to guarantee that node energy is not wasted due to too frequent retransmissions. Further, selection of shorter paths involving less number of nodes resulting in further saving of energy due to less number of nodes participating in packet forwarding.

With these objectives in mind, we have proposed the Forwarder Selection Function, FSF, a probability function to select the best forwarder node among the neighboring nodes of the current node, which is based on Pheromone Trail(PT) and heuristic function involving two parts representing Node Energy level(EN) and node link quality(LP) functions. Pheromone Trail(PT) represents the concentration of pheromone deposited on the path between the nodes (i.e., current node and its neighbor node) considering Energy, distance and link quality along the path (containing the link between current and neighboring nodes) from source to destination. In other words, higher PT represents the better good quality path from source node to the destination in terms of energy, distance and link quality. Node Energy (EN) function represents energy level of the neighbor node and Link quality(LP) function represents the quality of the link between the current node and the neighbor node under consideration.

Hence, the Forwarder Selection Function, FSF(ni, nj) to select the best forwarder node nj among the neighboring nodes of the current node ni can be defined as

$$FSF(n_i,n_j)= \begin{cases} \dfrac{[PT(n_i,n_j)]^{\alpha}[EN(n_j)]^{\beta}[LP(n_i,n_j)]^{\gamma}}{\sum_{n_j\in NBS(n_i)}[PT(n_i,n_j)]^{\alpha}[EN(n_j)]^{\beta}[LP(n_i,n_j)]^{\gamma}}, & if\ n_j\in NBS(n_i), \\ 0, & otherwise \end{cases} \quad -(1)$$

Where NBS(ni) represents the set of neighboring nodes of ni, PT(ni,nj) represents the concentration of pheromone deposited on the path between the nodes ni & nj, EN(nj) represents the energy level of the neighbor node nj.

LP(ni,nj) represents the quality of the link between nodes ni & nj, i.e., link probability. The Expected Transmission Count, ETX is a measurement of the transmission link which is calculated based on the past events occurred on that link. Then the link probability LP(ni, nj) between nodes ni & nj is given by the expression :

$$LP(n_i, n_j) = \frac{1}{ETX(n_i,n_j)} \qquad -(2)$$

α, β, γ are the parameters to control the significance or importance of pheromone trail of the path, node energy level and link quality between nodes. When $\alpha = \beta = \gamma = 1$, all three parameters PT, EN, LP are given equal

importance in the selection of the forwarder node. If one is interested in giving higher importance to PT, pheromone trail of the path, then one could $\alpha = 1, \beta = \gamma = 2$, similarly $\alpha = 2, \beta = 1, \gamma = 2$ to raise importance of EN, Node energy level or $\alpha = 2, \beta = 2, \gamma = 1$ to make importance of link quality more significant in the selection of forwarder node.

Let EI(nj) be the initial energy of node nj and ER(nj) be the Remaining (Actual) Energy of node nj, then the node energy level, EN(nj) is defined as

$$EN(nj) = \frac{ER(nj)}{EI(nj)} \quad \text{where} \quad ER(nj) > Eth \qquad -(3)$$

Threshold Energy, Eth is defined as the energy at which the node loses its right to participate in packet forwarding and is excluded from the path. Actual Energy of the neighboring node should be greater than the threshold Energy Eth in order to be considered for selection. Moreover, Eth can be used as a tunable parameter which can be varied depending on the traffic or load. For example, to conserve energy for later use and to perform load balancing, initially Eth can be raised to 50% of the Initial Energy EI so that most of the nodes will participate in packet forwarding/processing till the threshold energy is reached rather than some nodes getting depleted faster due to the prevailing higher importance attached to other two parameters. Later depending on the traffic or type of processing, Eth can be lowered to a reasonable value in order to extend the lifetime of the network.

It is to be noted that the Threshold Energy, Eth plays an important role in extending the lifetime of the network. Every node in the network is associated with an Eth Value. In order to save energy and prevent nodes from getting depleted fast, Eth of a node can be initially raised to a suitable higher percentage of the total energy of that node. This can be applied to all the nodes in the network or a group of nodes in a network depending on the traffic & type of processing. This helps in better energy balancing among neighboring nodes of a node of concern. When energy of all the neighboring nodes reach this threshold, then Eth can be lowered to an appropriate value, keeping in view that one of the quality neighbor nodes should always be available for packet forwarding. Or it can be set to the least minimum threshold (Eth_{min}) at which point node will stop participating in forwarding of packets due to energy depletion or disconnection from the network.

Pheromone Update Model:-
It has been observed that the amount of pheromone computed to be placed on the path during return journey is not proper to reflect that path as the optimal during the simulation period. Strongest path should have largest amount of pheromone whereas weakest path should have least amount of pheromone or almost zero. Among the competing stronger paths for selection, the variations in pheromone concentration should be such that always strongest path (i.e., optimal) is selected.

Keeping these in mind, pheromone update model has been designed considering the parameters the forward ant has collected during its travel from source to the destination. Once the forward ant reaches the destination, the following parameters collected by the forward ant are analyzed.

- Eavg, Average energy of the nodes in the path traversed by forward ant
- Emin, Minimum energy of the nodes in the path traversed by forward ant
- Nh_{sd} Distance travelled by the forward ant from source to destination, i.e., number of hops
- LP_{sd} Link quality of the path traversed by the forward ant from source to sink
- Pt_k be the path traversed by forward ant k from source to destination having $Nh_{sd}(Ptk)$ hops

Average ETX of the links in the path Ptk,
$$ETX_{av}(Ptk) = \frac{\sum_{i=1}^{Nhsd(Ptk)} ETXi}{Nhsd(Ptk)} \qquad -(4)$$

Average Link probabilities of path Pt_k,
$$LP(Ptk) = \frac{1}{ETXav(Ptk)} \qquad -(5)$$

Hence Link quality of the path (Ptk) is given by

$$\text{Path Link Quality, } PLQ(Ptk) = \frac{1}{ETXav(Ptk) * Nhsd(Ptk)}$$
$$= \frac{LP(Ptk)}{Nhsd(Ptk)} \qquad -(6)$$

The path Energy Quality is represented by the Average Energy, Eav, and minimum energy , Emin of the nodes along the path. Hence, Energy quality of path Ptk is given by the following expression :

$$\text{Path Energy Quality, PEQ(Ptk)} = \frac{\frac{E_{avg}}{E_{in}}}{} - (1 - \frac{E_{min}}{E_{avg}}) \qquad \text{-(7)}$$

Higher average energy and higher Minimum Energy of nodes along the path would yield a good quality path in terms of Energy.

The Pheromone update or the concentration of additional pheromone to be deposited is computed as given by the following expression :

$$\text{Path Energy Quality * Path Link Quality} \qquad \text{-(8)}$$
$$= \text{PEQ(Ptk) * PLQ(Ptk)}$$
$$= \left(\frac{E_{avg}}{E_{in}} - \left(1 - \frac{E_{min}}{E_{avg}}\right)\right) * \frac{LP(Ptk)}{Nhsd(Ptk)} \qquad \text{-(9)}$$

The equation (9) captures the impact of Average Energy and Minimum energy of the nodes along the shortest path with better path link quality on the concentration of pheromone deposition. In other words, Good quality shorter path with high average energy and higher value of minimum energy will result in more amount of pheromone to be deposited on that path rather than the path with low minimum and average energy.

Once the forward ant reaches the destination, ΔPT is computed using the parameter values provided by the forward ant and the forward ant is killed.

Next backward ant is created at the sink node with the computed ΔPT, $Nh_{sd.}$ The Pheromone updation is done by the backward ant in the reverse direction during its travel from destination node to source node.

For situations where nodes nearer to the destination node to have higher pheromone deposition when compared to nodes nearer to the source node in the path, the ΔPT computed in (9) is updated by the backward ant in the following fashion.

$$\Delta PT = \Delta PT * \left(1 - \frac{Nhcd - 1}{Nh_{sd}} \right) \qquad \text{-(10)}$$

Where Nh_{cd} is the number of hops from current node to the destination node during the traversal of the backward ant from destination to the source node.

Whenever a node ni receives a backward ant coming from a neighboring node nj, it updates $PT(ni,nj)$ in its routing table in the following manner:

$$PT(ni,nj) = (1 - \rho)PT(ni,nj) + \Delta PT \qquad \text{-(11)}$$

where ρ is a decay coefficient and (1- ρ) represents the evaporation of Pheromone trail since the last time $PT(ni,nj)$ was updated.

Performance Evaluation Metrics:-

In this section, we present the Performance Metrics used in the evaluation of our proposed Approaches : SIBER-ELP & SIBER-VLP.

Let NS be the total number of nodes in the network, TPR_d be the total number of packets received at the sink node, TPG_s be the total number of packets generated at the source node, SP_{TOT} be the total simulation period, EC_{ni} be the energy consumed by the node ni during the period of simulation SP_{TOT}, t_{ps} be the time at which a packet p is is generated at the source node and t_{pd} be that time at which that packet p is delivered at the sink node

Packet Delivery Ratio, PDR is defined as the ratio of total number of packets received at the sink node to the total number of packets generated at the source node.

$$\text{Packet Delivery Ratio PDR} = \frac{TPR_d}{TPG_s} \qquad \text{-(12)}$$

Total Energy Consumed, EC_{TOT} is defined as the Total energy consumed (in joules) by the nodes in the network during the period of simulation, SP_{TOT}

$$EC_{TOT} = \sum_{i=0}^{NS-1} ECni \qquad \text{-(13)}$$

Energy Efficiency is defined as the ratio of Total packets delivered at the destination to total energy consumed by the sensor nodes in the network.

$$EE = \frac{TPR_d}{EC_{TOT}} = \frac{PDR * TPG_s}{EC_{TOT}} \qquad \text{-(14)}$$

Latency, **L** is defined as the difference in time when a packet is generated at the source node and when it eventually gets delivered at the sink node, that is nothing but the time delay of a packet sent from the source node to reach the destination node.

$$\mathbf{L} = t_{pd} - t_{ps} \qquad \text{-(15)}$$

Standard Deviation σ is defined as the average variation between energy levels of all nodes in the network (in joules)

$$\sigma = \sqrt{\frac{\sum_{i=0}^{NS-1}(ELni - \mu)^2}{NS}} \qquad \text{-(16)}$$

where NS is the total number of nodes in the network, ELni is the energy level of node ni in the network and μ is the mean of the energy levels of all the nodes in the network. ELni is nothing but the remaining Energy (i.e., Current Energy) of node ni denoted by ERni.

Simulation Setup, Results and Discussion:-

Our proposed system SIB-XLP was simulated using open source NS-2 simulator. In this simulation, we have considered static and dynamic network scenarios with random topology wherein nodes are randomly distributed. In the case of dynamic network scenario, we have considered Random way-point mobility model with nodes having the ability to move with a specified speed. Our proposed approaches SIB-ELP and SIB-VLP are compared with most commonly used technique in the literature EEABR for varying network sizes(dimension) – 25, 49 64 and 100 nodes. It is assumed that all the methods use the same data rate. The performance evaluation metrics used in this simulation are Packet Delivery Ratio, Latency, Dropped packets, Average Energy Consumed, Average Energy Remaining, Average Minimum Available Energy, Energy Efficiency(Kb/J), and Standard Deviation.

Simulation Setup – Static Scenario

The simulation parameters used in the simulation study are shown in Table 1.

Table 1 : Static Scenario - Simulation Parameters

Parameter	Value	Parameter	Value	Parameter	Value
Scenario	Static	Initial Energy	30J	Data Traffic	CBR
Topology	Random	Transmitting Energy	1.0mW	Data Rate	50Kbps
Number of Nodes	25, 49, 64, 100	Receiving Energy	0.5mW	α	1
Area	400 X 400, 600 X600, 700 X700, 900X900	Packet Size	1000 bytes	β	1
Transmission Radius	250 meters	Bandwidth	11MB	γ	1
Propagation Model	TwoRayGround	Simulation Time	100 sec	ρ	0.2

Routing Protocols Compared are SIBER-VLP, SIBER-ELP, EEABR Performance Metrics used are Packet Delivery Ratio, Latency, Dropped packets, Average Energy Consumed, Average Energy Remaining, Average Minimum Available Energy, Energy Efficiency(Kb/J), Standard Deviation.

Results and Discussion – Static Scenario:-

In static scenario, all nodes including the destination node are fixed. Our proposed approaches SIB-ELP and SIB-VLP are compared with EEABR for varying network sizes – 25, 49 64 and 100 nodes and the results for each network size are presented in the following sections.

Static Scenario – Network Size=100 Nodes:-

As it is seen from fig. 1a) SIBER-VLP exhibits extremely high performance by having a very high Packet Delivery Ratio or high success rate of delivering the packets to the destination. The packet drops for SIBER-VLP is less because of the selection of high quality paths and high link probability nodes for packet transmission throughout the simulation period. For SIBER-ELP, the packet drops are moderate from the beginning due to large network size and increase at 60 seconds due to the path changes in the network to maintain a high quality path with more number of hops. EEABR shows high increase in packet drops throughout simulation period. SIBER-VLP shows on an average a high success rate of 99.9%, followed by SIBER-ELP with a success rate of 84.37% where as EEABR shows very poor performance with an average success rate of 28.84%.

As shown in figs. 1d) & 1e) SIBER-ELP consumes more energy than SIBER-VLP from the beginning and further increases at 60 seconds as it selects a high quality path with more number of hops than before. SIBER-VLP performs well even for a larger network since it only considers the paths having a high quality and high link probability. EEABR performs worst because more number of nodes are involved in the packet transmission. As the network consumes more energy in EEABR, the remaining energy and minimum available energy become low, which is making it less efficient than SIBER-ELP and SIBER-VLP. Whereas SIBER-VLP turns out be more energy efficient.

As far as Energy efficiency is concerned (fig 1c)), SIBER-VLP outperforms both SIBER-ELP and EEABR due to the selection of   high quality paths and high link probability nodes always. Efficiency of SIBER-ELP decreases at 60 seconds and again after 10 seconds slightly increases because an alternate path has been selected at 60 seconds where the hop count is greater than the previous path hop count. In EEABR, efficiency seems to increase for some 10 seconds, but decreases at 30 seconds due to more number of nodes involved in the packet transmission. It still decreases at 50 seconds because of nodes consuming more energy and more packet drops.

As evident from figure 1b), SIBER-ELP takes more time to send packets to the sink at the start of the simulation because of large network size. But later it uses a better optimal path decreasing latency. Finally, it uses a high quality path having less number of hops, thereby reducing the end to end delay. SIBER-VLP has a very low delay as it only uses high quality path and high link probability nodes in the packet transfer. EEABR presents more delay due to more packet drops and high energy consumption. As seen in fig 1f), the standard deviation is low in both SIBER-VLP and SIBER-ELP, but is not the case in EEABR.

Static Scenario - Network Size=64 Nodes:-
It is clear from fig 2a) that   SIBER-VLP has very low packet drops when compared to SIBER-ELP and EEABR as it always chooses a high quality path and high link probability nodes. Packet drops increase in the SIBER-ELP at 50 seconds of simulation because there is a path change at this moment having more number of nodes in the path to select a high quality path. EEABR has higher increase in packet drops when compared to SIBER-VLP. SIBER-VLP shows on an average a high success rate of 99.9%, followed by SIBER-ELP with an improved success rate of 92.03% and EEABR though exhibiting poor performance with an improved average success rate of 75.66% which is much better than network with 100 nodes.

As seen in figs 2c), 2d) & 2e), the paths used in SIBER-ELP and SIBER-VLP are the same till 50 seconds which are optimal paths, but after that period SIBER-ELP has a deviation consuming more energy than SIBER-VLP because of selecting a high quality path containing more number of nodes than before. SIBER-VLP shows better performance in terms of energy conservation compared to SIBER-ELP and EEABR protocol. This clearly shows that Energy efficiency of SIBER-VLP is better than SIBER-ELP and EEABR. SIBER-ELP shows a good result till 50 seconds and then decreases. EEABR consumption of more energy makes it less energy efficient. As the network consumes more energy in EEABR, the remaining energy and minimum available energy is low, which is making it less efficient than SIBER-ELP and SIBER-VLP.

Latency for SIBER-ELP (fig 2 b)) shows that as the time increases the path selected with high quality path nodes may vary in hops leading to different delay times. But at 50 seconds it is clear that it uses a high quality path with less number of hops. This difference is not seen in SIBER-VLP as it uses good quality path and high link probability nodes with less number of hops throughout the simulation. EEABR presents a high latency when compared to other protocols because it selects the nodes in the path not having high average or minimum energy, which may result in a decrease in network lifetime because of the nodes having low energy participating in the transmission.

It is seen from fig 2f), after 50 seconds there is much deviation in node energy levels for SIBER-ELP, whereas SIBER-VLP has a low standard deviation throughout the simulation. EEABR has a high deviation when compared to other two protocols.

Static Scenario – Network Size NS=49 Nodes:-
Packet drops are very less in SIBER-VLP because of the forwarder selection function choosing its high quality path and high link probability nodes in the path selection. The packet drops are increased after 50 seconds in SIBER-ELP because the path selected is a longer high quality path and nodes having high link probability. The more packet drops in EEABR makes it a less efficient protocol because of the improper pheromone deposition on the path traversed by the ants. As the packet drops are more in EEABR, the packet delivery ratio decreases. In SIBER-ELP, the packet delivery ratio is initially high like SIBER-VLP, but decreases slightly after 60 seconds. SIBER-VLP exhibits a high packet delivery ratio. As evident from fig 3a), SIBER-VLP shows on an average a high success rate of 99.9%, followed by SIBER-ELP with an improved average success rate of 98.97 where as EEABR shows very poor performance with an average success rate of 49.84%

It is seen from figs. 3c), 3d) & 3e), in SIBER-ELP and SIBER-VLP, Energy Efficiency slightly decreases at 50 seconds because of a path change which is having more number of hops, but again it increases at 60 seconds. EEABR has very low energy efficiency because the packets are transferred in the path which are not having a high quality. As the network consumes more energy in EEABR, the remaining energy and minimum available energy are low, which is making it less efficient than SIBER-ELP and SIBER-VLP. As evident from 3b), Latency of SIBER-VLP is very low from the beginning of simulation, but slightly increases at 50 seconds due to the path change having more number of hops. After 10 seconds again it remains same due to optimal path selection throughout the simulation. The standard deviation is a very low value for SIBER-ELP and SIBER-VLP compared to EEABR as shown in in fig 3f).

Static Scenario – Network size NS=25 Nodes:-
As seen in fig 4a), Packet drops are very less in the three models due to small network size. All the three models perform better throughout the simulation with low packet drops and high packet delivery ratio.
 Latency is the time needed by a source to send a packet to sink, which is very low for SIBER-VLP (see fig 4b)) when compared to SIBER-ELP and EEABR since it always selects a high quality path and high link probability nodes. In SIBER-ELP, Latency gradually decreases at 60 seconds because at this juncture the path selected is a high quality path with less number of hops. In EEABR, it selects a sub-optimal path which experiences more delay as it does not take into account high quality path and high link probability.

Energy efficiency of a network is based on the number of packets received and the total energy consumed by the network. Even though similar behavior is observed in all the three models with respect to packet delivery ratio and dropping of the packet, it is keen to observe from fig 4c) that SIBER-VLP consumes very less energy compared to the other two models, SIBER-ELP and EEABR. When SIBER-ELP is compared to EEABR, its performance improves after 70 seconds of simulation due to less number of hops with high quality path and which is not taken into account by EEABR as its deposition of pheromone is not proper in the selected path by ants. So, EEABR selects a suboptimal path which consumes more energy than SIBER-ELP and SIBER-VLP. As a result, it can be concluded that SIBER-VLP is more energy efficient protocol compared to SIBER-ELP and EEABR.
It is clear from figs d) & e) that SIBER-VLP has a high Minimum Available Energy and high Remaining Energy compared to SIBER-ELP and EEABR. As seen from 4f), there is a same distinctive standard deviation for SIBER-VLP as the nodes with high energy levels participate in the routing. In SIBER-ELP, there is still less deviation after 60 seconds, since the path selected has less number of hops than before. In EEABR, the deviation is low throughout the simulation.

From these results, it can be concluded that EEABR performs reasonably well for smaller Network sizes but shows very poor performance when network size is high. SIBER-ELP shows higher performance in terms of packet delivery ratio, latency and Energy Efficiency when compared to EEABR. SIBER-VLP is the most preferred protocol as it exhibits very high delivery ratio as high as 99.9%, and most energy efficient with least latency.

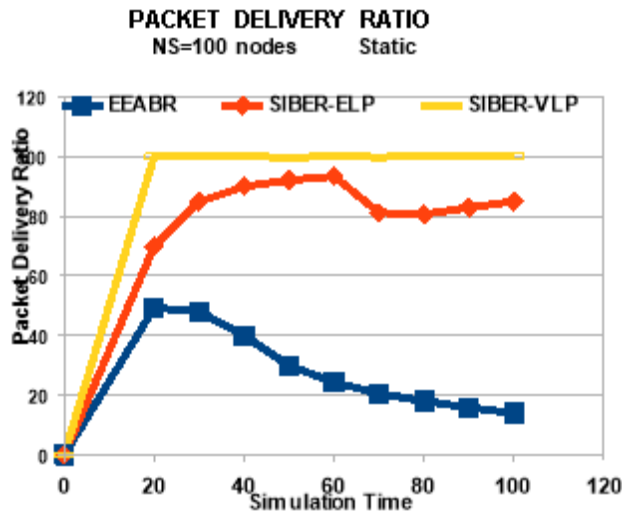**Fig 1a) : Packet Delivery Ratio vs time (static Scenario 100 nodes)**

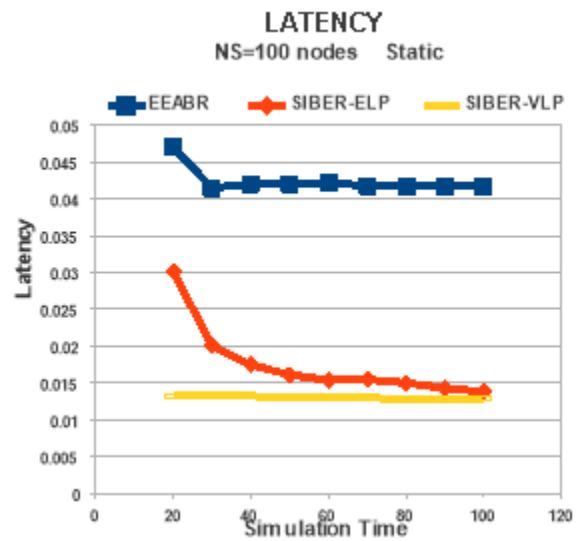**Fig 1b) : Latency vs time (static Scenario 100 nodes)**

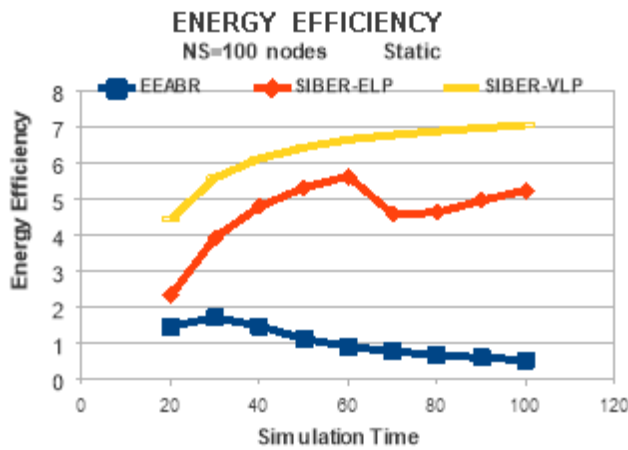**Fig 1c) : Energy Efficiency vs time (static Scenario 100 nodes)**

Fig 1d) : Remaining Energy vs time (static Scenario 100 nodes)
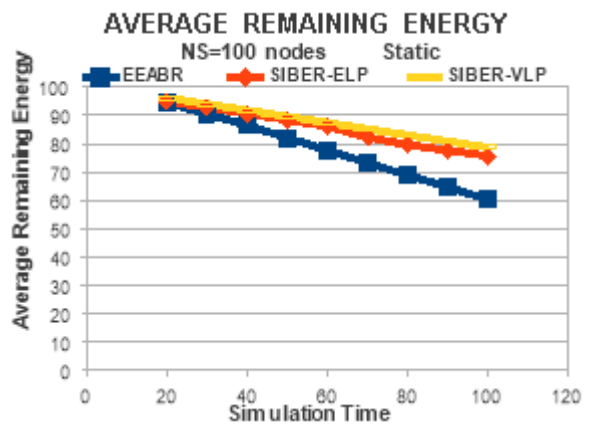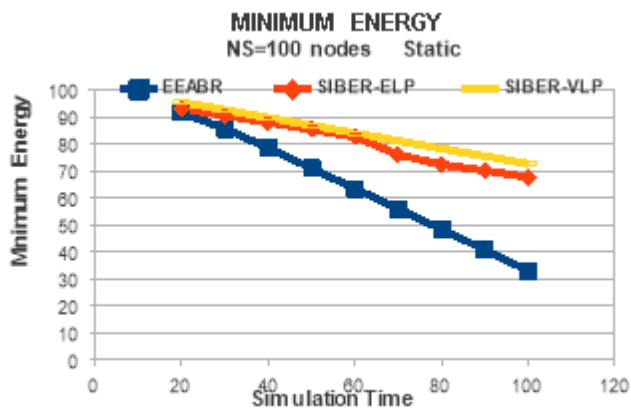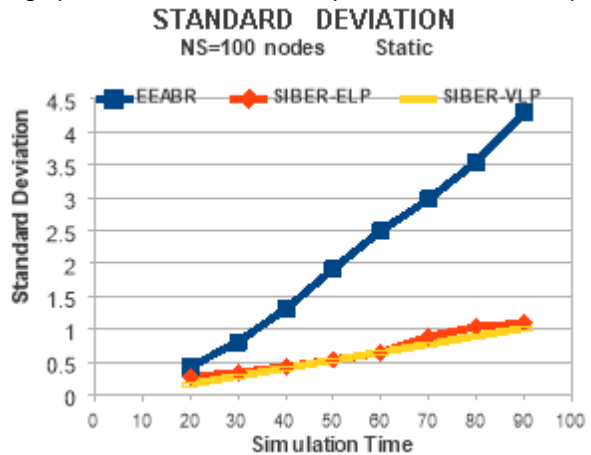

Fig 1e) : Minimum Energy vs time (static Scenario 100 nodes)

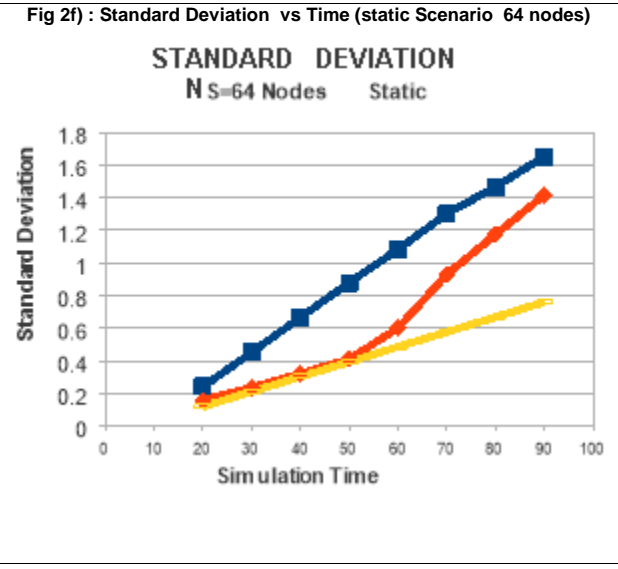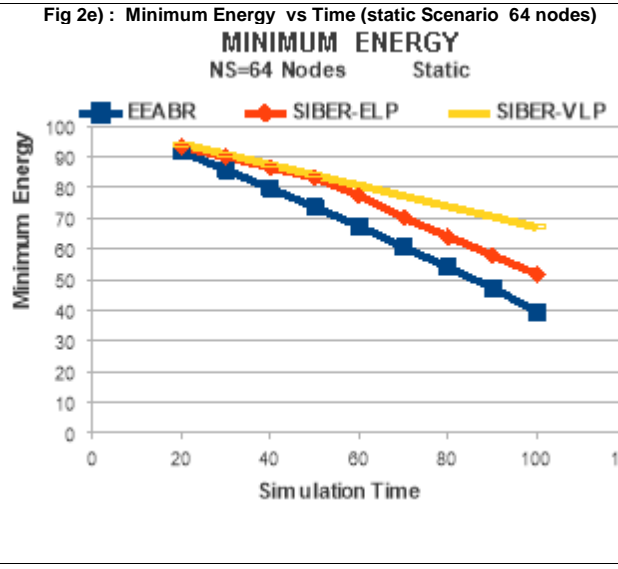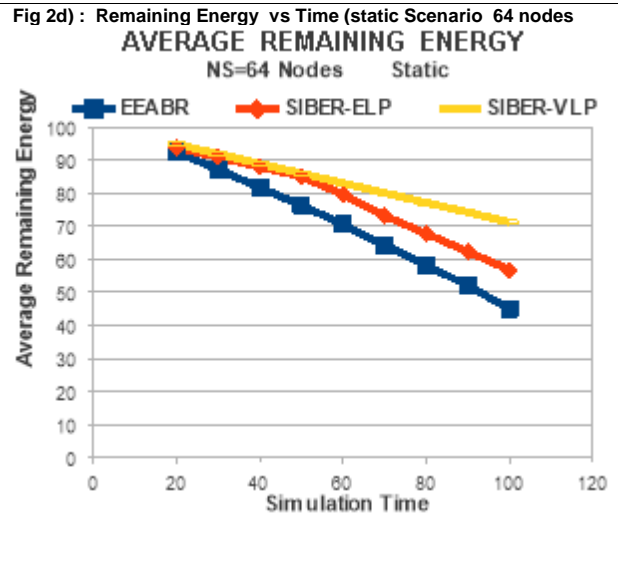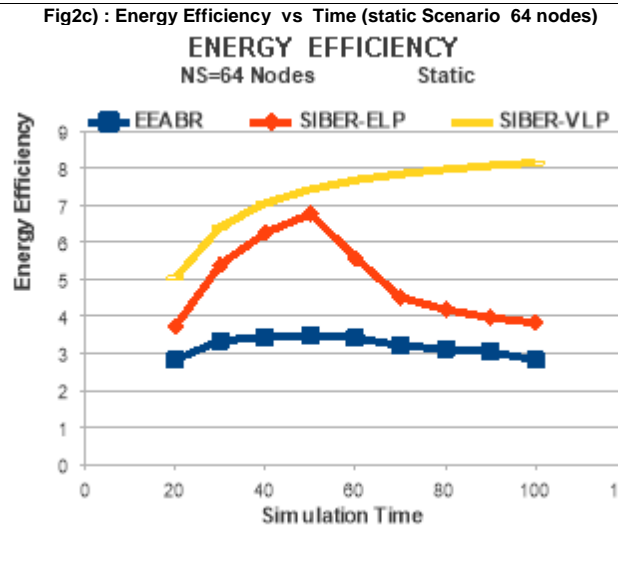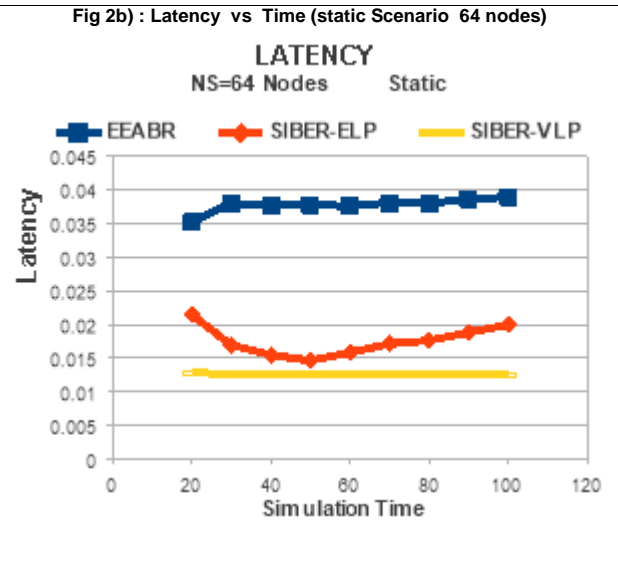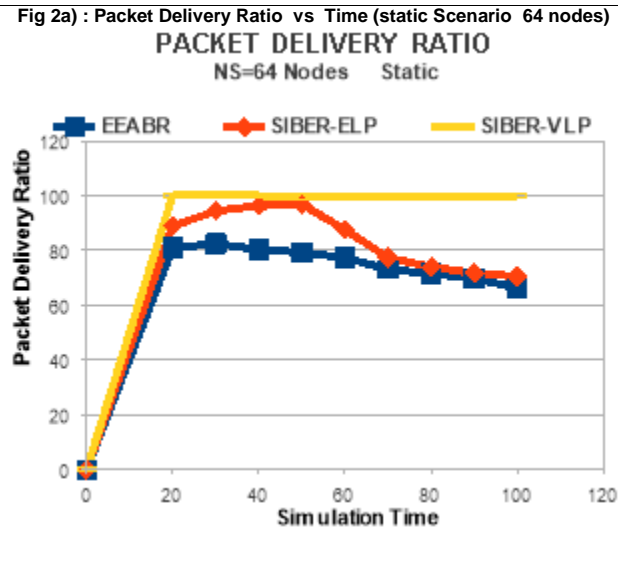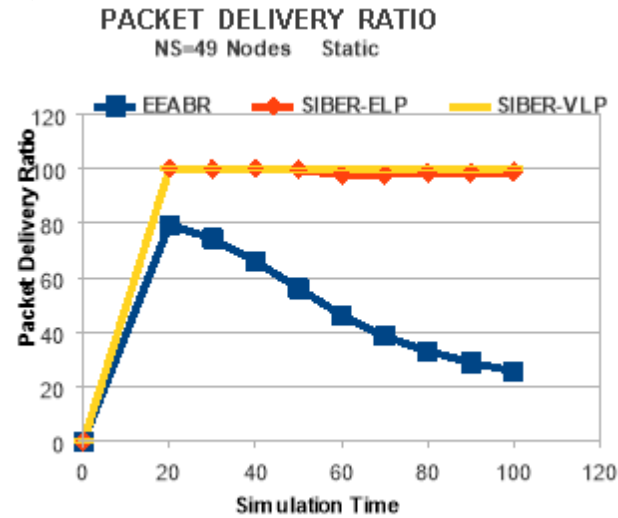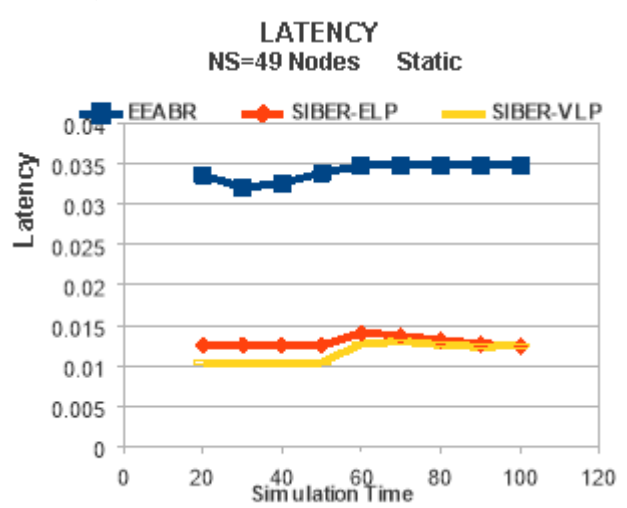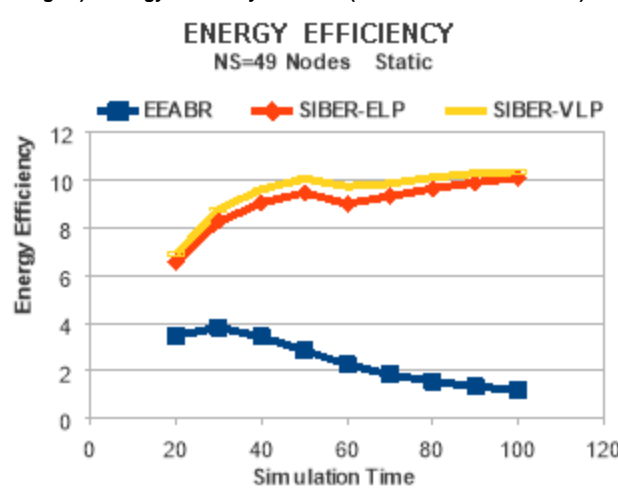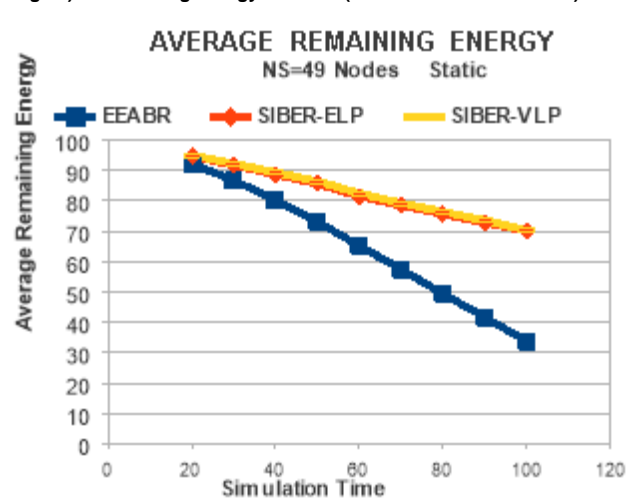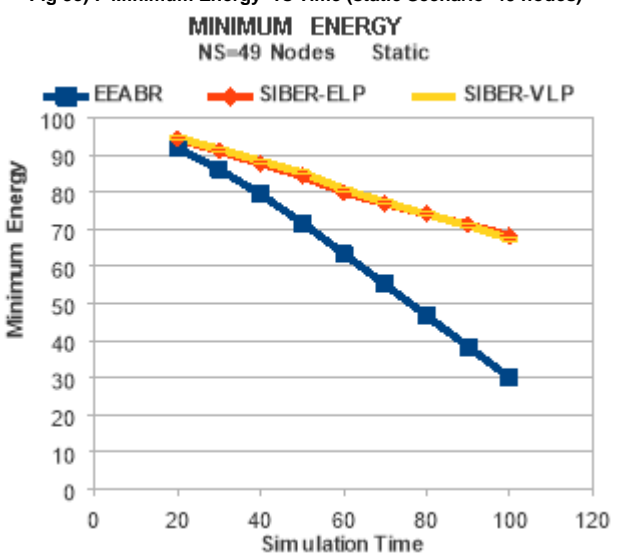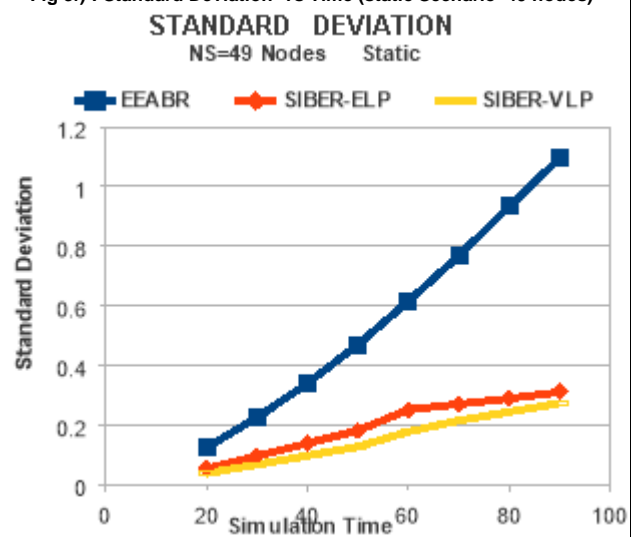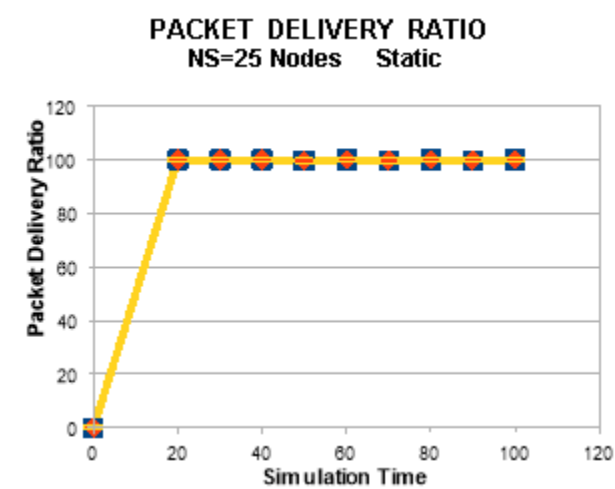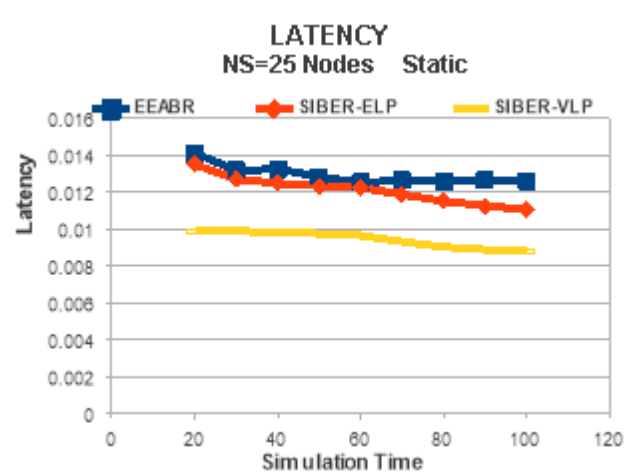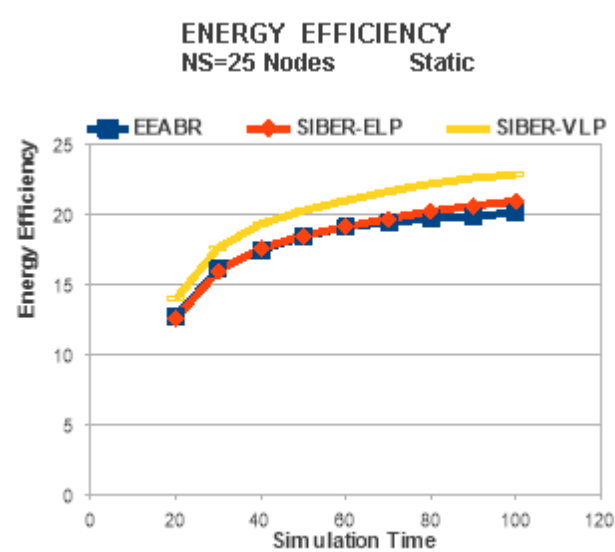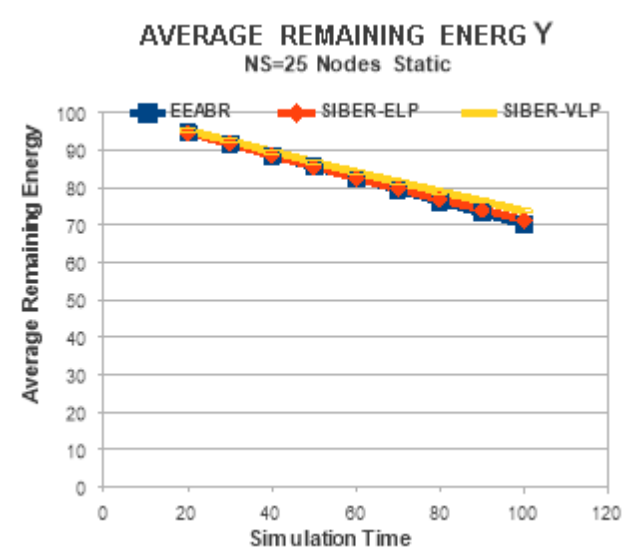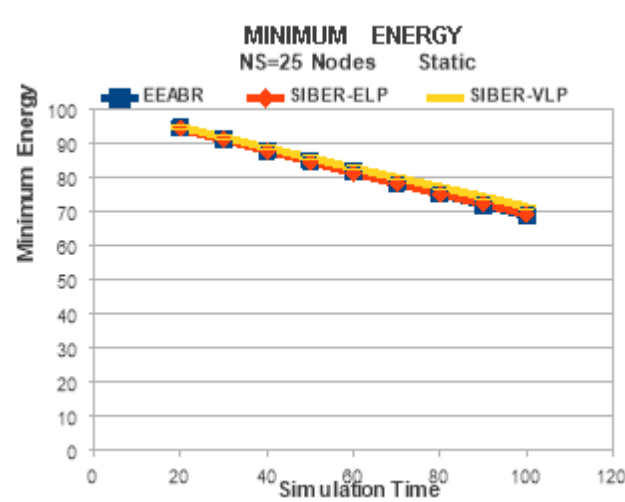**Fig 1f) : Standard Deviation vs time (static Scenario 100 nodes)**

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Fig 2a) : Packet Delivery Ratio vs Time (static Scenario 64 nodes)

Fig 2b) : Latency vs Time (static Scenario 64 nodes)

Fig2c) : Energy Efficiency vs Time (static Scenario 64 nodes)

Fig 2d) : Remaining Energy vs Time (static Scenario 64 nodes

Fig 2e) : Minimum Energy vs Time (static Scenario 64 nodes)

Fig 2f) : Standard Deviation vs Time (static Scenario 64 nodes)

Fig 3a) : Packet Delivery Ratio vs Time (static Scenario 49 nodes)

Fig 3b) : Latency vs Time (static Scenario 49 nodes)

Fig 3c) : Energy Efficiency vs Time (static Scenario 49 nodes)

Fig 3d) : Remaining Energy vs Time (static Scenario 49 nodes)

Fig 3e) : Minimum Energy vs Time (static Scenario 49 nodes)

Fig 3f) : Standard Deviation vs Time (static Scenario 49 nodes)

Fig 4a) : Packet Delivery Ratio vs Time (static Scenario 25 nodes)

Fig 4b) : Latency vs Time (static Scenario 25 nodes)

Fig 4c) : Energy Efficiency vs Time (static Scenario 25 nodes)

Fig 4d) : Remaining Energy vs Time (static Scenario 25 nodes)

Fig 4e) : Minimum Energy vs Time (static Scenario 25 nodes)

Fig 4f) : Standard Deviation vs Time (static Scenario 25 nodes)
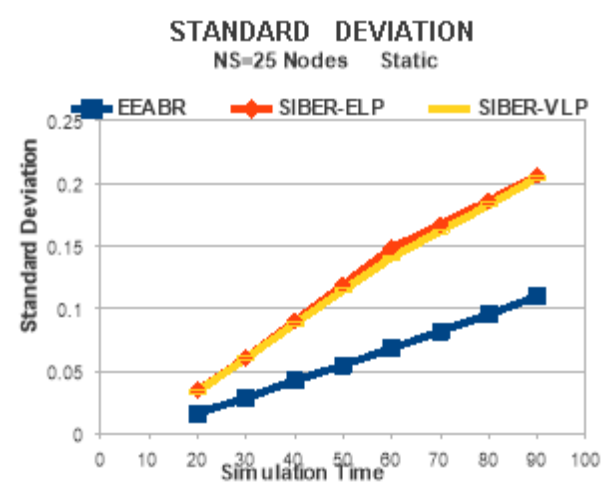
Simulation Setup – Dynamic Scenario:-
The simulation parameters used in the simulation study are shown in Table 2. Routing Protocols Compared are SIBER-VLP, SIBER-ELP, EEABR. Performance Metrics used are Dropped packets, Average Energy Consumed, Average Energy Remaining, Minimum Available Energy, Energy Efficiency(Kb/J), Packet Delivery Ratio, Latency, Standard Deviation

Table 2 :- Dynamic Scenario - Simulation Parameters

Parameter	Value	Parameter	Value	Parameter	Value
Scenario	Dynamic	Initial Energy	30J	Data Traffic	CBR
Topology	Random	Transmitting Energy	1.0mW	Data Rate	50Kbps
Number of Nodes	25, 49, 64, 100	Receiving Energy	0.5mW	α	1
Area	400 X 400, 600 X600, 700 X700, 900X900	Packet Size	1000 bytes	β	1
Transmission Radius	250 meters	Bandwidth	11MB	γ	1
Propagation Model	TwoRayGround	Simulation Time	100 sec	ρ	0.2
Mobility Model	Random Way-Point Model	Node Movement	Sink Node	Pause Time	15 seconds
		Speed	5m/sec		

Results and Discussion – Dynamic Scenario:-
In dynamic scenario, all nodes except the sink node are fixed. Sink node moves at a speed of 5m/sec with a pause time of 15 secs. It is to be noted here that in static scenario, since all nodes are fixed, there will be fixed number of paths from source to sink. Where as in dynamic scenario, since destination is mobile, there will be more number of paths when compared to static environment. Our proposed approaches SIB-ELP and SIB-VLP are compared with EEABR for varying network sizes – 25, 49 64 and 100 nodes and the results for each network size are presented in the following sections.

Dynamic Scenario- Network Size NS=100 Nodes:-
As it is seen from fig. 5a) SIBER-VLP exhibits extremely high performance by having a very high Packet Delivery Ratio or high success rate of delivering the packets to the destination even in dynamic scenario. Packet drops in SIBER-VLP is very low when compared to SIBER-ELP and EEABR as it always chooses a high quality path and high link probability nodes. Packet drop increases for SIBER-ELP and which is a constant packet drop during the simulation because there is not much difference in hop count of the path selected which is a high quality path. EEABR has a large increase in packet drops as the simulation time increases.

As shown in 5d) & 5e), in SIBER-ELP, SIBER-VLP and EEABR, energy consumption increases with time. SIBER-VLP shows better performance in terms of energy conservation compared to SIBER-ELP and EEABR protocols (see fig 5c)). As the network consumes more energy in EEABR, the remaining energy and minimum available energy become low, which is making it less efficient than SIBER-ELP and SIBER-VLP.

Latency for SIBER-ELP in fig 5b) shows that as the time increases the path selected with high quality path nodes may vary in hops leading to different delay times. But at 30 seconds it is clear that it uses a high quality path with less number of hops. This difference is not seen in SIBER-VLP as it uses good quality path and high link probability nodes with less number of hops throughout the simulation. EEABR presents a high latency when compared to other protocols because it selects the nodes in the path not having high average or minimum energy, which may result in a decrease in network lifetime because of nodes having low energy participating in the transmission. As seen in fig 5f), SIBER-VLP and SIBER-ELP both have low standard deviation throughout the simulation. EEABR has a high deviation when compared to other two protocols.
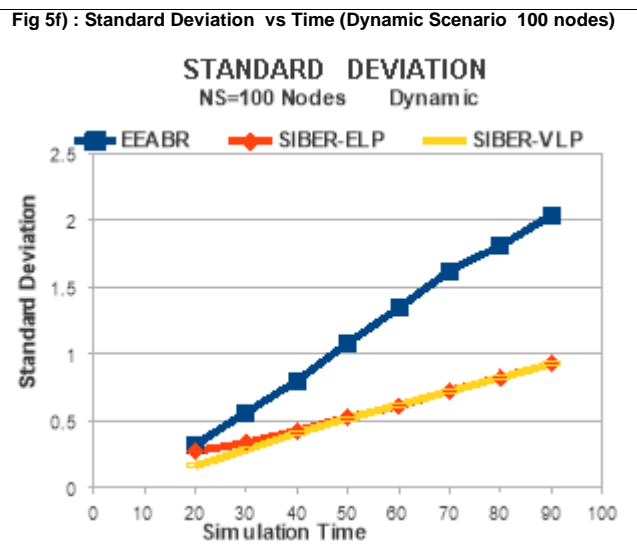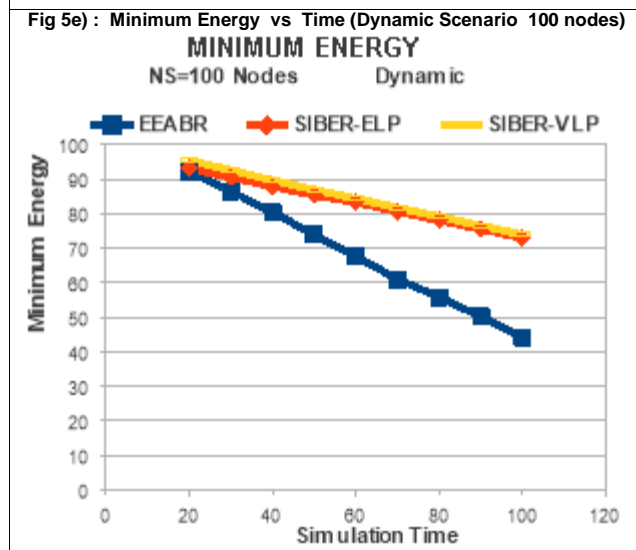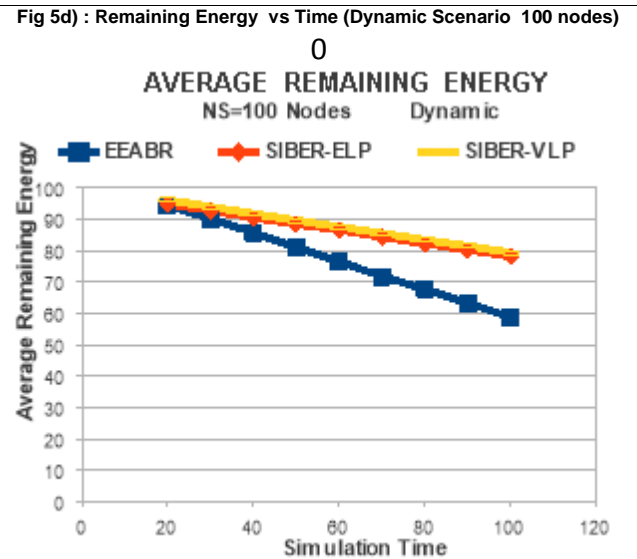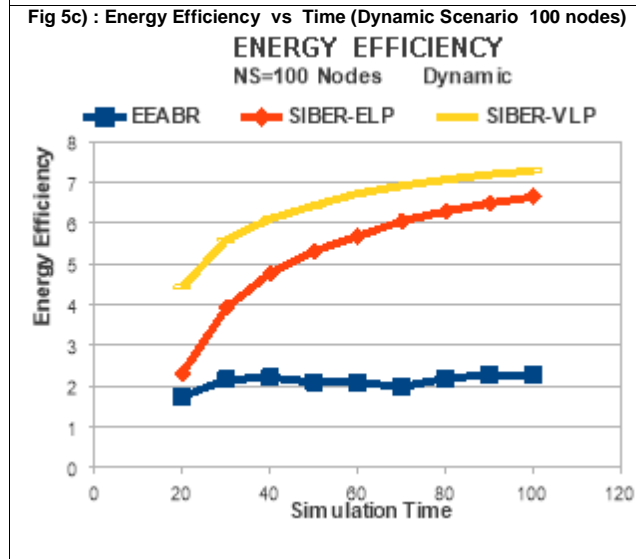
Dynamic Scenario- Network Size NS= 64 Nodes:-
It is seen from fig 6a), Packet drops in SIBER-VLP is very low when compared to SIBER-ELP and EEABR as it always chooses a high quality path and high link probability nodes. Packet drops increases for SIBER-ELP and which is a constant packet drop during the simulation because there is not much difference in hop count of the path selected which is a high quality path. EEABR has a large increase in packet drops as the simulation time increases.
As shown in figs. 6c), 6d) & 6e), in SIBER-ELP, SIBER-VLP and EEABR, energy consumption increases with time. SIBER-VLP shows better performance in terms of energy conservation compared to SIBER-ELP and EEABR

protocol. As the network consumes more energy in EEABR , the remaining energy and minimum available energy get low, which is making it less efficient than SIBER-ELP and SIBER-VLP.

Latency for SIBER-ELP in 6b) shows that as the time increases the path selects high quality path nodes which may vary in hops leading to a different delay times. But at 30 seconds it is clear that it uses a high quality path with less number of hops. This difference is not seen in SIBER-VLP as it uses a good quality path and high link probability nodes with less number of hops throughout the simulation. EEABR presents a high latency when compared to other protocols because it selects the nodes in the path not having high average or minimum energy, which may result in a decrease in network lifetime because of the nodes having low energy participating in the transmission.

It is clear from fig 6f) that SIBER-VLP and SIBER-ELP have low standard deviation throughout the simulation. EEABR has a high deviation when compared to other two protocols.

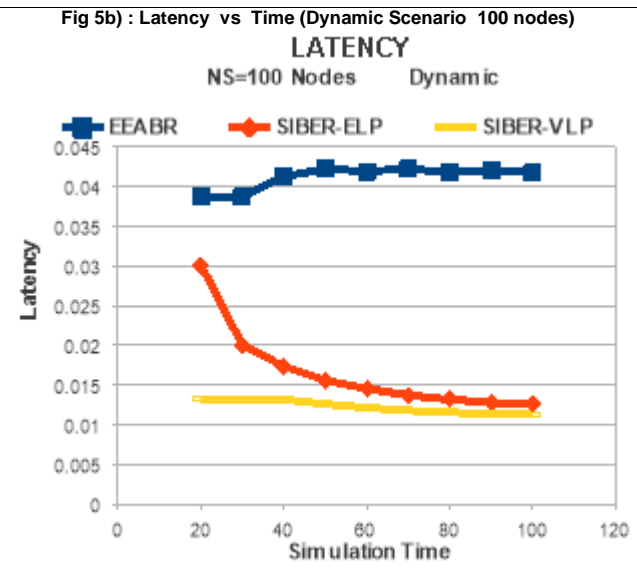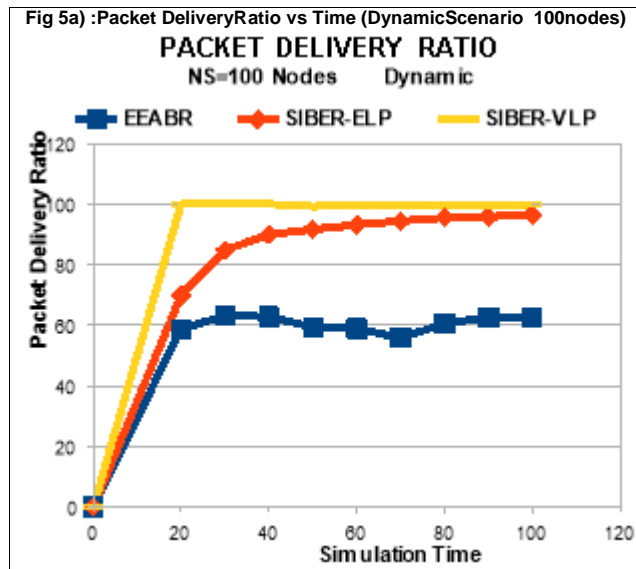**Dynamic Scenario - Network Size NS= 49 Nodes:-**

As seen in fig 7a), Packet drops are very less in SIBER-VLP because of the forwarder selection function choosing its high quality path and high link probability nodes in the path selection. The packet drops are increased between 60 & 70seconds in SIBER-ELP because the path selected is a longer high quality path. The more packet drops in EEABR presents it as a less efficient protocol because of the improper pheromone deposition on the path traversed by the ants. As the packet drops are more in EEABR, the packet delivery ratio decreases. In SIBER-ELP, the packet delivery ratio is initially high like SIBER-VLP, but decreases between 60 & 70 seconds as it is the time where the network chooses a longer path having a high quality. SIBER-VLP presents a high packet delivery ratio.
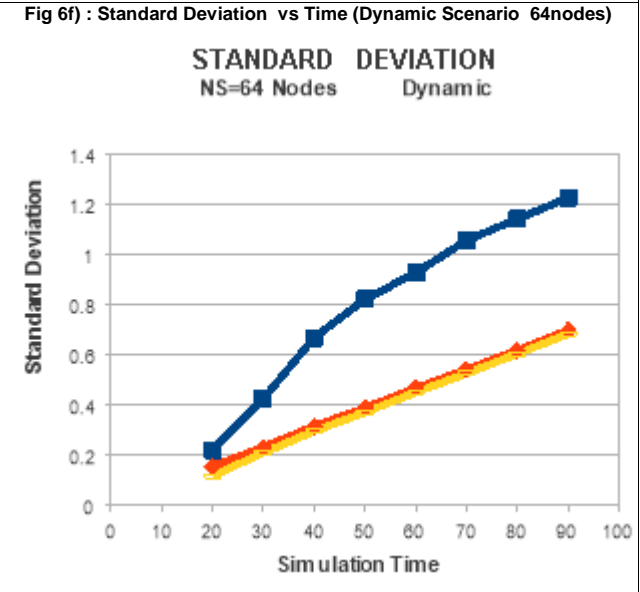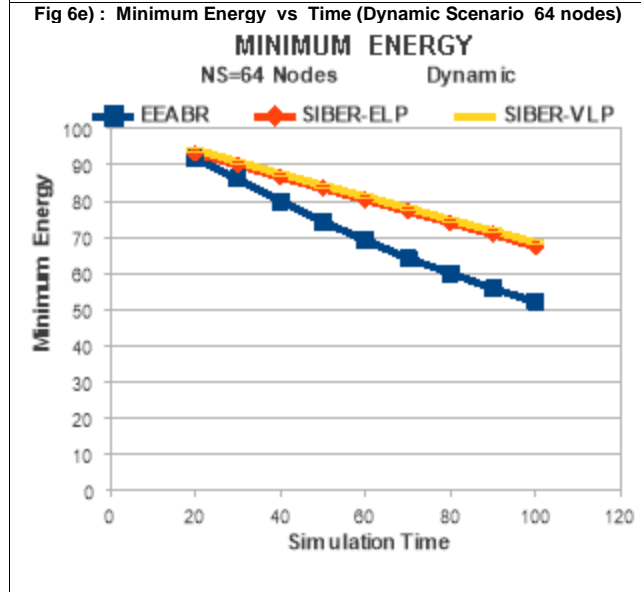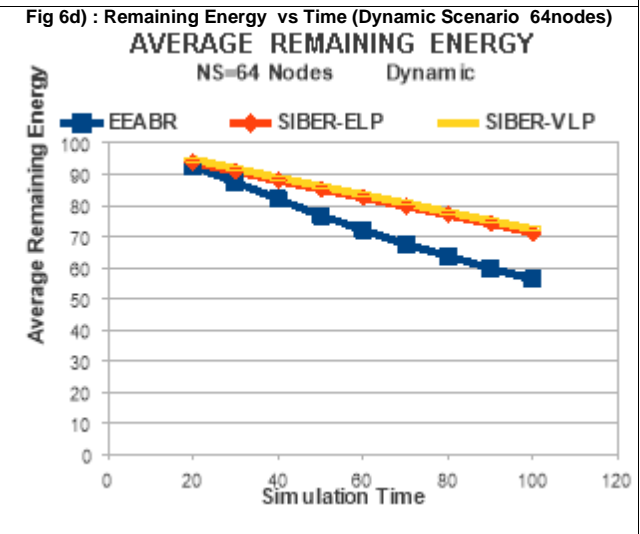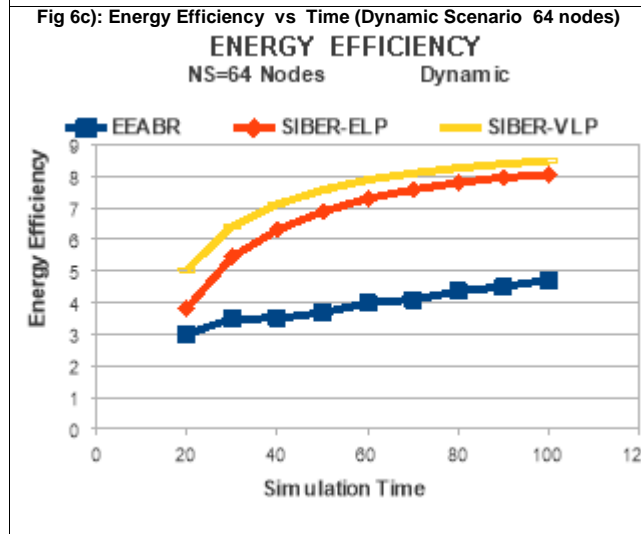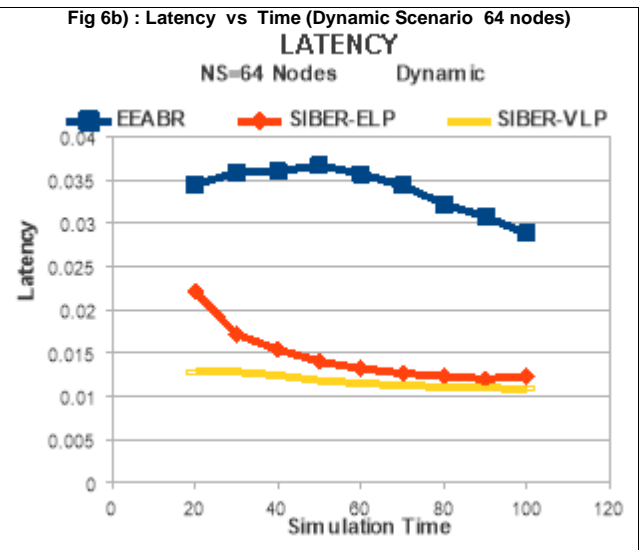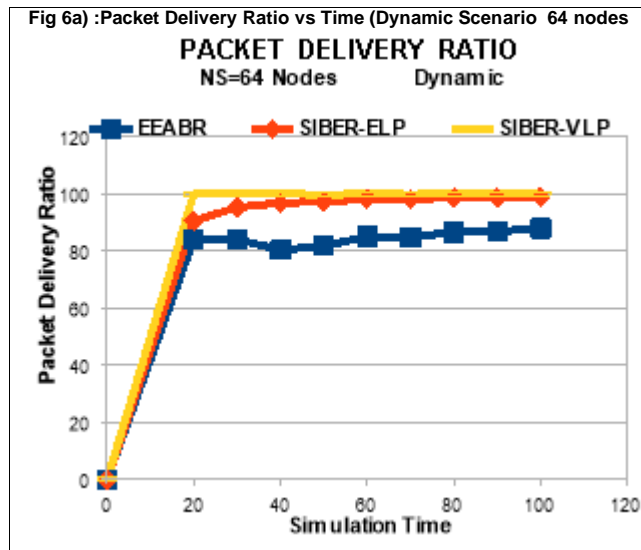
As shown in fig 7c), 7d) & 7e), in SIBER-VLP, Energy Efficiency slightly decreases after 50 seconds because of a path change which is having more number of hops, but again it increases after 60 seconds. In SIBER-ELP, Energy Efficiency decreases after 60 seconds because of a path change which is having more number of hops, but again it increases after 70 seconds. In EEABR, the efficiency is low because the packets are transferred in the path which are not having a high quality. As the network consumes more energy in EEABR,, the remaining energy and minimum available energy is low, which is making it less efficient than SIBER-ELP and SIBER-VLP. As shown in fig 7b), Latency of SIBER-VLP is very low from the beginning of simulation, but slightly increases at 50 seconds due to the path change having more number of hops. After 10 seconds again it remains same due to optimal path selection throughout the simulation. Latency of SIBER-ELP is also low from the beginning of simulation, but slightly increases at 60 seconds due to the path change having more number of hops. After 10 seconds again it decreases and remains constant after 90 seconds. It is seen from 7f) that the standard deviation is a very low value for SIBER-ELP and SIBER-VLP compared to EEABR. There is a slightly high deviation for SIBER-ELP between 60 to 70 seconds because more number of nodes are involved in the simulation as they are having a high quality path.

Dynamic Scenario- Network Size NS=25 Nodes:-

As shown in 8a), Packet drops are very less in the three models due to small network size. All the three models perform better throughout the simulation with low packet drops and high packet delivery ratio. Latency is the time needed by a source to send a packet to sink, which is very low for SIBER-VLP till 30 seconds, and after that it increases slightly because of the high link probability nodes becoming less energy efficient. So, an alternate path is chosen with increase in delay to have high quality path. As seen in fig 8b), in SIBER-ELP, Latency gradually decreases at 30 seconds because at this juncture the path selected is a high quality path with less number of hops. In EEABR, it selects a sub-optimal path which experiences more delay as it does not take into account high quality path and high link probability. Energy efficiency of a network is based on the number of packets received and the total energy consumed by the network. Even though the similar behavior is observed in all the three models with respect to delivery ratio and dropping of the packet, it is very keen to observe that SIBER-VLP consumes very less energy compared to the other two models, SIBER-ELP and EEABR(see figs 8c), 8d) & 8e)) . When SIBER-ELP is compared to EEABR, its performance upgrades after 30 seconds of simulation due to less number of hops with high quality path and which is not taken into account by EEABR as its deposition of pheromone is not proper in the selected path by ants. So, EEABR selects a suboptimal path which consumes more energy than SIBER-ELP and SIBER-VLP.

As a result, it can be concluded that SIBER-VLP is more energy efficient protocol compared to SIBER-ELP and EEABR. It is clear from the observation that SIBER-VLP has a high Minimum Available Energy and high Remaining Energy compared to SIBER-ELP and EEABR. SIBER-ELP, SIBER-VLP and EEABR have low standard deviation(see fig. 8f)).
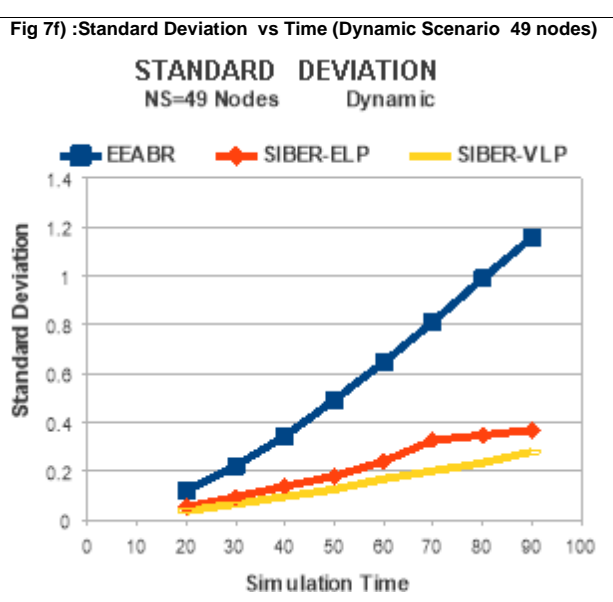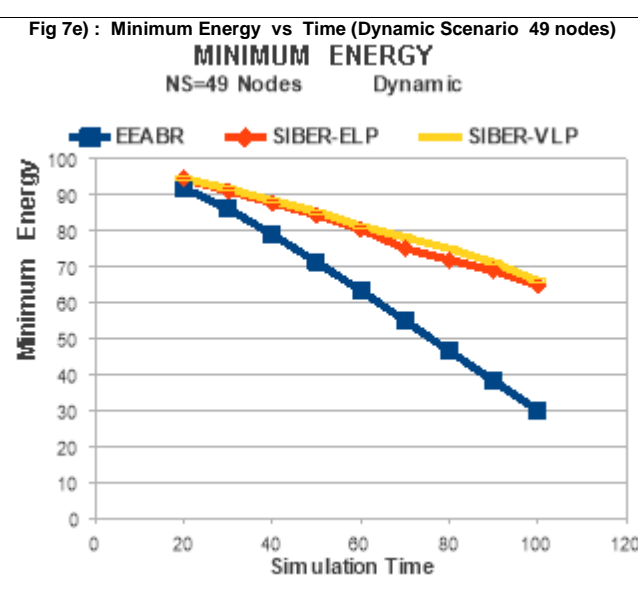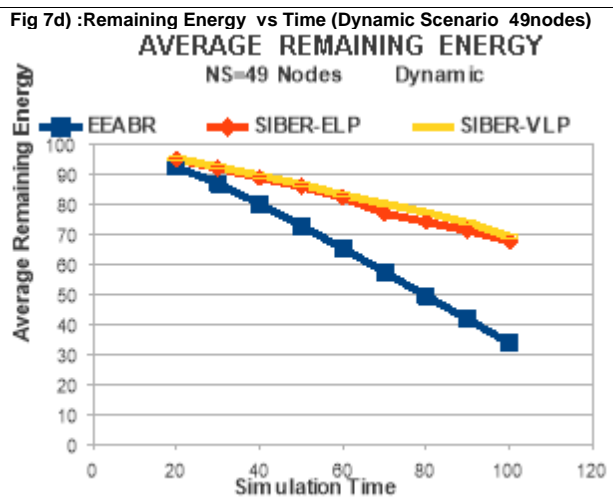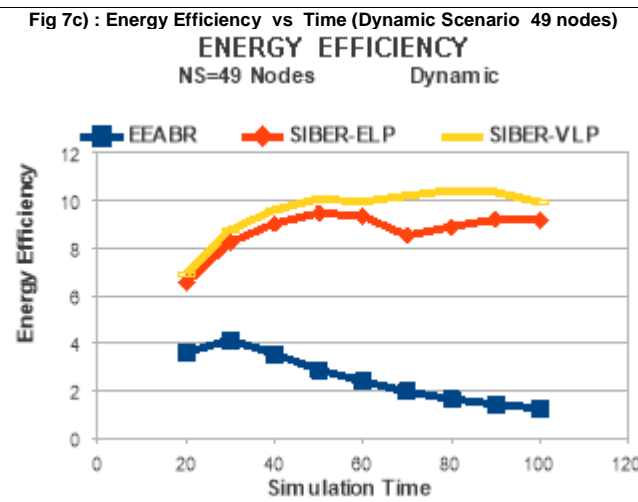
Fig 5a) :Packet DeliveryRatio vs Time (DynamicScenario 100nodes)

Fig 5b) : Latency vs Time (Dynamic Scenario 100 nodes)

Fig 5c) : Energy Efficiency vs Time (Dynamic Scenario 100 nodes)

Fig 5d) : Remaining Energy vs Time (Dynamic Scenario 100 nodes)

Fig 5e) : Minimum Energy vs Time (Dynamic Scenario 100 nodes)

Fig 5f) : Standard Deviation vs Time (Dynamic Scenario 100 nodes)
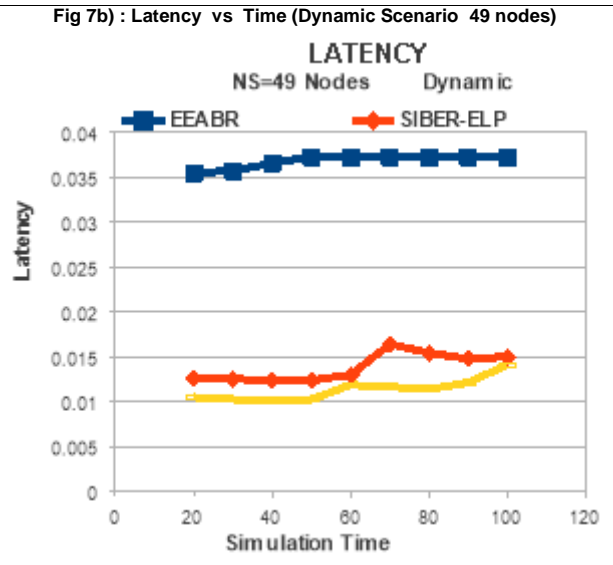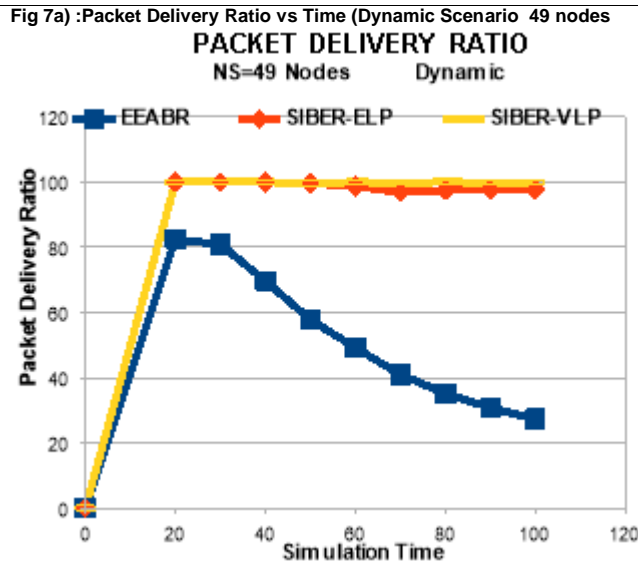
Fig 6a) :Packet Delivery Ratio vs Time (Dynamic Scenario 64 nodes)

Fig 6b) : Latency vs Time (Dynamic Scenario 64 nodes)

Fig 6c): Energy Efficiency vs Time (Dynamic Scenario 64 nodes)

Fig 6d) : Remaining Energy vs Time (Dynamic Scenario 64nodes)

Fig 6e) : Minimum Energy vs Time (Dynamic Scenario 64 nodes)

Fig 6f) : Standard Deviation vs Time (Dynamic Scenario 64nodes)

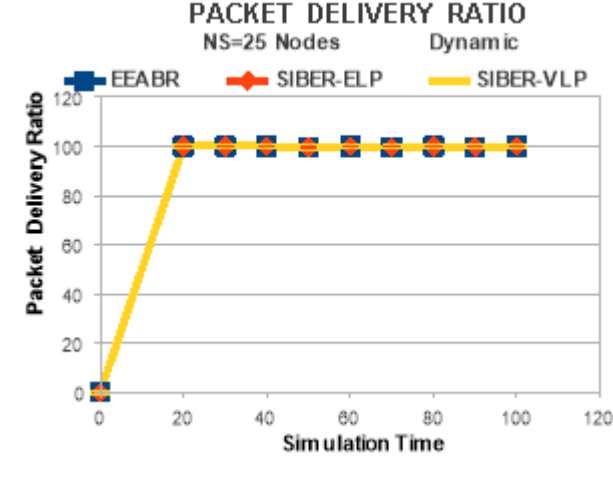Fig 7a) :Packet Delivery Ratio vs Time (Dynamic Scenario 49 nodes)

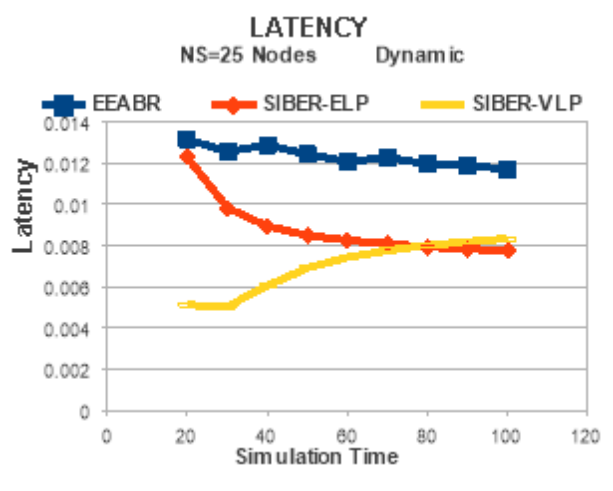Fig 7b) : Latency vs Time (Dynamic Scenario 49 nodes)

Fig 7c) : Energy Efficiency vs Time (Dynamic Scenario 49 nodes)

Fig 7d) :Remaining Energy vs Time (Dynamic Scenario 49nodes)

Fig 7e) : Minimum Energy vs Time (Dynamic Scenario 49 nodes)

Fig 7f) :Standard Deviation vs Time (Dynamic Scenario 49 nodes)

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Fig 8a) :Packet Delivery Ratio vs Time (Dynamic Scenario 25 nodes

Fig 8b) : Latency vs Time (Dynamic Scenario 25 nodes)

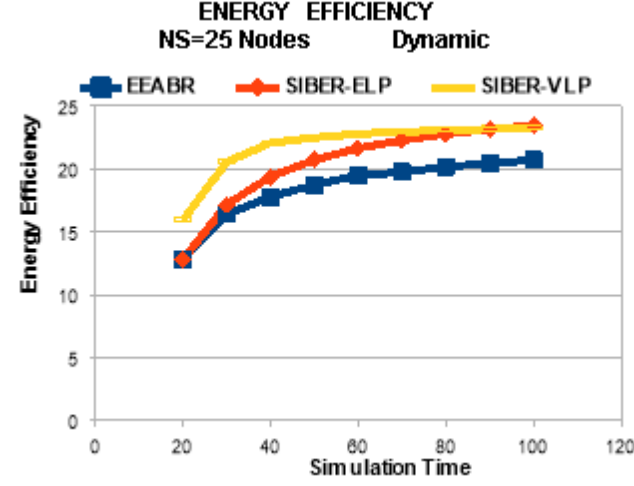**Fig 8c) : Energy Efficiency vs Time (Dynamic Scenario 25 nodes)**

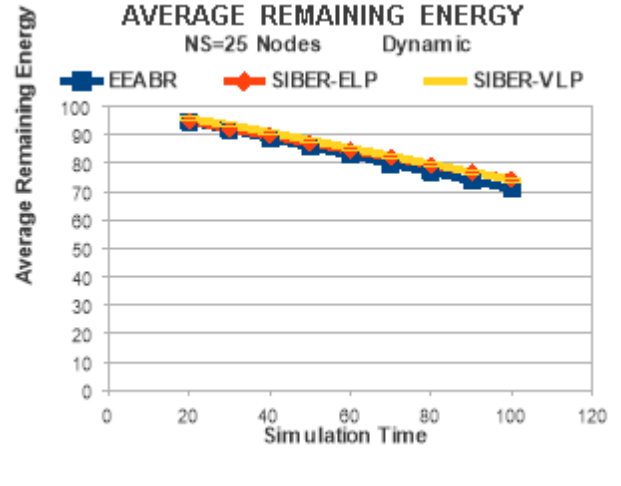**Fig 8d) : Remaining Energy vs Time (Dynamic Scenario 25 nodes)**

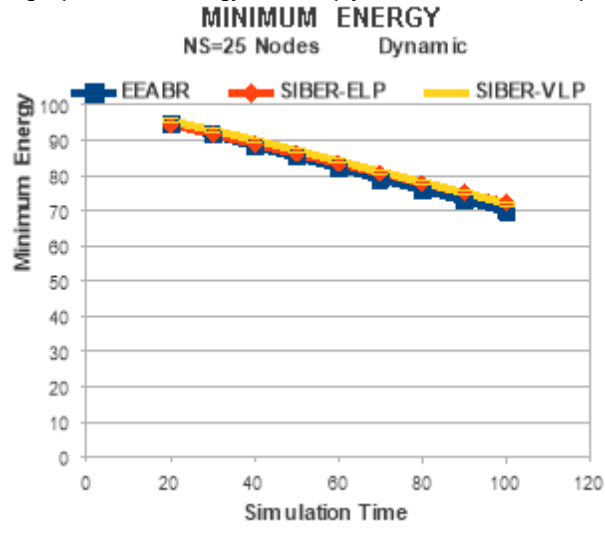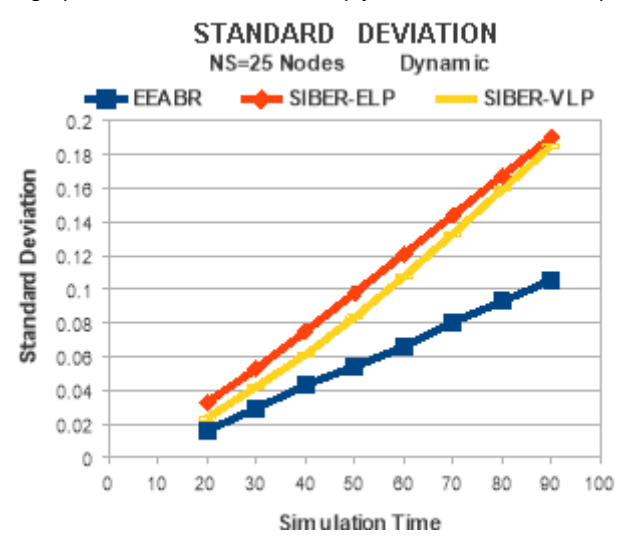**Fig 8e) : Minimum Energy vs Time (Dynamic Scenario 25 nods)**

Fig 8f) : Standard Deviation vs Time (Dynamic Scenario 25 nodes)

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Conclusion:-

In this paper, we have presented our proposed work Swarm intelligence based Efficient Routing protocol for Wireless Sensor Networks, SIBER-XLP with improved Pheromone Update model and optimal Forwarder Selection function which takes into account Link quality of the path along with Energy, distance to select the best quality path from source to sink for packet forwarding. Using NS-2 simulator, we have performed performance evaluation of our model (two variants – SIBER-ELP (Equal Link Probability) & SIBER-VLP (Variable Link Probability)) and compared with EEABR by considering both static and dynamic scenarios with varying networking sizes – 25, 49, 64 and 100. Our simulation results indicate that SIBER-XLP performs extremely well in terms of Packet Delivery Ratio, Energy Efficiency and latency in both static and dynamic scenarios. EEABR performs reasonably well for smaller Network sizes but shows very poor performance when network size is high. SIBER-ELP shows higher performance in terms of packet delivery ratio, latency and Energy Efficiency when compared to EEABR whereas SIBER-VLP performs extremely well when compared to both with very high packet delivery ratio (success rate), high energy efficiency and least latency (end to end delay). From simulation results, it can be concluded that SIBER-VLP is the most preferred efficient protocol as it exhibits very high delivery ratio as high as 99.9%, and higher energy efficiency with least latency and highly suited for harsh environments. As a future work. we are currently extending this work to incorporate security with trust awareness to tackle insider attacks which is the most critical requirement of harsh environments.

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