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Utilizing Multilayer Hierarchical Structure in Context Aware Routing Protocol for Wireless Sensor Networks

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Abstract. Applications of Wireless Sensor Network (WSN) have been extended in numerous diverse fields. Most of these applications require data accuracy and longer service. Therefore, energy efficiency is one of the key requirements. In this paper, we have proposed an energy efficient routing protocol, Context Aware Multilayer Hierarchical Protocol (CAMHP) which is context aware and utilizes multilayer hierarchical structure to cover more area and to distribute energy consumption across the network. Moreover, efficient techniques are employed to reduce data traffic and to share cluster head role among the nodes. Simulation results show significant amount of energy efficiency and better service length compare to Low Energy Adaptive Clustering Hierarchy (LEACH) and Multi-Hop model.

Keywords: Wireless Sensor Network, hierarchical routing protocol, context awareness.

1 Introduction

Rapid development of Micro-Electro-Mechanical Systems (MEMS) is making wireless communication more affordable and applicable to a number of diverse fields. In that follow through, Wireless Sensor Network (WSN) has reached to a certain pick of development regardless of its intrinsic constraints. However, energy efficiency remains as a vital research focus due to the nature of WSN applications [6]. Researchers emphasis on various techniques to improve energy efficiency

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such as circuitry enhancement, load balancing, minimization of operational activities. The energy consuming operations of sensor nodes are identified as sensing the environment, sending and receiving of data, processing of query request, forwarding data to neighbors [19]. On the contrary, some activities often become the cause of energy wastage such as idle listening to the media, retransmission of packets due to collision, processing of too many control packets. So minimizing such activities as well as optimizing routing to attain energy efficiency has been a key research objective in the field of WSN.

In some comprehensive surveys on routing protocols of WSN [1,23], a good number of protocols have been investigated. Based on the underlying network structure, these protocols can be divided into three categories such as flat, hierarchical and location based. In a typical hierarchical routing protocol, sensors are grouped into a number of clusters, each of which has a local point of access - the cluster head. In a cluster, the cluster head is usually one of the member nodes or in some cases, a multi –antenna node with special techniques [24]. Member nodes send sensed data to the cluster head, and the cluster head forwards or aggregates and forwards the data to the base station. Such a hierarchy can be single layered or multiple layered. Certainly, the hierarchical approach allows greater area coverage and offers inherent optimization capabilities. On the contrary, this technique may encounter some difficulties like data latency and self induced black hole effect [7].

A number of protocols [6,11,12,13] have been proposed that utilize the benefits of the hierarchical approach. Some of these protocols show significant improvements compared to the previously proposed protocols. However, in forming the cluster, one significant aspect has been unnoticed until recently. This aspect is the context of the environment the nodes are supposed to sense. The abovementioned protocols' cluster formations are based on statistical assumption or sensor characteristics or even in a random manner. Considering the real world phenomena that the context of the environment can be grouped into a number of ranges, can constitute in formation of the clusters. Thus, this attribute can be efficiently utilized in the cluster formation and optimize normal operations. Some of the recent publications [9,20] reflect the applicability of such technique. In this paper, we propose a routing protocol called the Context Aware Multilayer Hierarchical Protocol (CAMHP) which is based on the context of the environment. The key objective of our proposition is to attain maximum energy efficiency in routing activities as well as network operability in a wider area. The application of context awareness in cluster formation greatly improves the data handling and data aggregation. For more optimization, packets containing the same value as previous iteration are not sent by the nodes. This reduces the data traffic between cluster heads and nodes significantly. Again, the three layer hierarchical approach actually ensures greater area coverage compare to flat routing protocols.

The paper is organized as follows: in the Section 2, key issues of current routing protocols are discussed. In Section 3, the CAMHP is described in detail with prior assumptions and explained terminologies. In Section 4, the simulation result of CAMHP is presented with comparison, and Section 5 concludes the paper with future direction.

2 Key Issues of Related Works

Protocol design constraints are quite stiff for WSN because of the design architecture of sensor nodes. This ultimately forces researchers to design protocols as simple as possible. One of the simplest routing protocols is the single hop model. But this model has proved to be impractical, because distant nodes will be out of energy quickly due to long range communication. Furthermore, in an WSN of thousand nodes, the base station and nearer nodes will have to deal with frequent signal collisions and heavy packet losses. The multi hop model is considered as a more improved and better performed model. It has larger area coverage, less collision possibility and a novel data aggregation capability. A number of protocols has been proposed based on the multi hop model [8, 12,15]. But it also suffers some drawbacks such as high latency time and self induced black hole effect [7]. The cluster-based hierarchical approach offers a number of advantages over other models. Compared to the multi hop model, it has less latency and more data optimization capability. In cluster based model, data are aggregated by the cluster heads unlike by every intermediate node in multi hop model. This facility makes cluster based protocol more suitable for time crucial applications also. Furthermore, data traffic is less prone to collision near the base station.

Among the proposed hierarchical protocols, some protocols detect the cluster boundary with the help of a central coordinator [17] or manually chosen by the network planner [2]. Some other protocols use the predefined location information to form the clusters [3,10]. Low Energy Clustering Hierarchy (LEACH) is one of the most referred protocols among hierarchical protocols in WSN. In a number of literatures, LEACH has been considered as the benchmark for performance measurement. It has some distinct characteristics like self configuration, localized control of data transmission, data compression and aggregation capability. It has some basic assumptions such as fixed location of the base station and predefined ratio of cluster heads among all nodes. This protocol utilizes the random cluster head role rotation technique to distribute energy consumption across the network. Nodes in the network are grouped into some clusters. One node from each cluster is selected as the cluster head. The cluster head is supposed to receive data from other nodes of the cluster, then aggregate and forward to the base station. All the communications are single hop and direct. LEACH has shown substantial performance achievement compared to its predecessor protocols. However, it has some drawbacks also. For example, applying a probabilistic value to select cluster heads may cause selection of a number of cluster heads from a smaller geographic region.

The framework of LEACH has been utilized in development of other protocols [12,25]. In [12], Power Efficient Gathering in Sensor Information System (PEGASIS) has been proposed that uses a greedy algorithm to construct a chain. Each node only transfers packets to the closest node on the same chain. But it inherits the limitations of the multi hop model such as excessive delay for distant nodes. Again, a single leader can be a bottleneck for the whole network. LEACH has an extended version, LEACH-C with centralized control [5]. Some of the contemporary protocols are roughly based on such idea [22]. However, centralized control actually infringes the distributed architectural approach for WSN and may create a single point of failure.

The term "Context-awareness" has been introduced in the computational world more than a decade ago in [16]. However, its aspects have not been utilized in WSN until recently. In [9], authors have proposed a "Context Adaptive Clustering" protocol which forms clusters of sensor nodes with similar output data within the bound of given tolerance parameter. Moreover, a simple data aggregation technique has been employed without generating large errors. The expected advantage of this protocol is less energy consumption and prolonged active service. This protocol has shown significant performance improvement where the environmental context is quite gradual. However, the cluster head role has not been effectively distributed which might cause early energy exhaustion of some nodes. Besides, if the environmental phenomenon is changing rapidly, this protocol might not be a feasible one.

In some other context aware proposal [18], Data-Aware Clustering Hierarchy (DACH) has been presented where sensors are clustered based on both distance and data distribution. To achieve more accuracy and efficiency, a multi-granularity query processing technique has been employed in DACH. In the simulation results, DACH has been compared with LEACH and shows longer active service and more accuracy. However, a deeper exploration of DACH has revealed some unnoticed issues. For example, high residual cluster heads are selected based on the energy information. Prior to the protocol initialization, the only way to gather such information is through broadcasting. This might greatly affect on the energy efficiency. Again, DACH has proposed a multilevel hierarchy which might need some careful optimization. Unless, in certain situations, the cluster head role might be performed by the same node in different levels. This occurrence might cause energy exhaustion for such nodes prior to other nodes.

In a more recent publication [21], Context-Aware Clustering Hierarchy (CACH) has been proposed where context-awareness is fully utilized to construct clustering hierarchies. Moreover, techniques are applied for equal distribution of energy consumption across the network and to reduce data traffic. Performance evaluation of this protocol shows significant improvement in energy efficiency compare to LEACH. However, this two layered hierarchical protocol can only cover the area within any node's maximum transmission range.

3 Context Aware Hierarchical Approach

Our proposed protocol is a context-aware cluster based hierarchical protocol. It consists of three layer hierarchies and the architecture is entirely distributed, that means no central control or manual configuration. Thus, the network is self configured upon deployment and proceeds with autonomous coordination and operations. Nodes are grouped into a number of clusters and those clusters form a super cluster with specific exceptions. In the following sub-sections, the proposed protocol's assumptions, terminologies and algorithm are described in detail.

3.1 Assumptions

In our proposed protocol, some of the parameters and environmental characteristics have been assumed as a priori. Firstly, the environmental data have regional properties. Such environmental data can be obtained by measuring contexts like temperature, humidity or light intensity. To be more specific, there are distinguishable differences between data of every region (cluster). Secondly, the ratio of cluster heads among other nodes is predetermined. For example, 5% of the total nodes are cluster heads at any given time. Thus nodes are aware of the number of clusters on the network. Finally, nodes are assumed to quasi-stationary. However, smooth movement does not hinder the normal operations at all.

3.2 Terminologies

In this paper, we have used some terms that are briefly described as below:

- Cluster: Groups of sensor nodes classified into the same context of the environment.
- Cluster head: A common node with special duty. Its duties include forming the cluster, receiving data from member nodes, aggregation of data and sending the aggregated data to the super cluster head.
- Member nodes: Nodes that are members of a cluster but not a cluster head nor a super cluster head.
- Designated area for candidates: The area from where a node can hear cluster head advertisements from all the cluster heads of the network.
- Candidate nodes: Nodes that fall within the designated area. These nodes are eligible to become a super cluster head. However, these nodes can never be a cluster head.
- Super cluster head: A candidate node that complies with the rule for super cluster head role rotation technique. In the selected round, it receives packets from the cluster heads, then aggregates and forwards to the base station. Other than the selected round, it is a common node acting as a member node.
- Data aggregation: Aggregating the received data from nodes and transforming those into a single packet. This operation is performed by the cluster heads and the super cluster head.
- Slot: The TDMA time slot when an individual member node transmits its sensed data to the cluster head. The slot time of each member node in a single cluster is equal and mutually exclusive.
- Frame: A frame contains all individual TDMA slots for member nodes of a cluster. After end of every frame, the cluster heads send aggregated data to the super cluster head.
- Round: A round is the time span that includes the set up phase and the consecutive steady phase. The number of frames within a round is set as 10 for our proposal. In the Fig. 1, slot, frame and round are shown in the time domain.
- Setup phase: After the initial deployment, nodes enter into the setup phase. Cluster heads and a

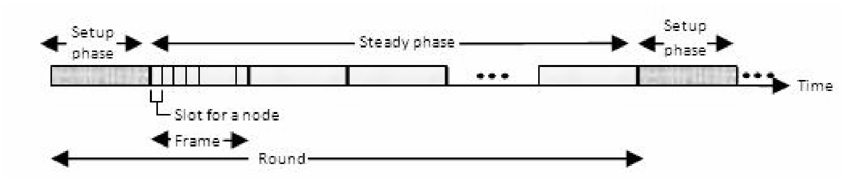

Fig. 1. Time distribution of the proposed protocol

super cluster head are selected, cluster heads prepare and disseminate the TDMA schedule and member nodes fix their slots according to the schedule. In the beginning of later rounds, the whole network invokes the setup phase again.

- Steady phase: As setup phase finishes, nodes enter into the steady operation phase. This phase usually consists of a number of consecutive frames. In the proposed protocol, the lifetime of the network is divided into a series of equal length time spans called round. Within every round, the initial portion is allocated for the set up phase. The later and longer portion is reserved for the steady operation phase in which data are transmitted from member node.

3.3 Algorithm

After the initial deployment, nodes are activated in an asynchronous manner and enter into the setup phase. The steps are described below in a sequential style.

- Step 1: Nodes sense the environment and save the data temporarily. At this point, there is no hierarchy between nodes. Every node checks whether any cluster head advertisement has been received with the same context value as itself. If so, the node sends a join request message to that cluster head. For this round, this is a member node. If not, the node declares itself as a cluster head and broadcast a cluster head advertisement message. Then it waits join request messages for a certain period. In a worst case scenario, there might not be any join request message heard within this period which indicates that there are no member nodes for this cluster. In such case, the cluster head proceeds with only one member node which is itself. However, this is a rare case to happen where a good number of nodes are deployed.
- Step 2: After the certain period for the exchange of advertisement and join messages, the member nodes check whether it has heard cluster head advertisement from all the cluster heads. If so, it enlists itself as a candidate node and again checks whether it has received any super cluster head advertisement or not. If so, the candidate proceeds with the duties of a member node. If not, it declares itself as a super cluster head and broadcasts this message. This message is processed by the cluster heads only and assists them to identify the super cluster head. If a node has not heard cluster head advertisements from all the cluster heads, it proceeds with the normal duties of a member node.

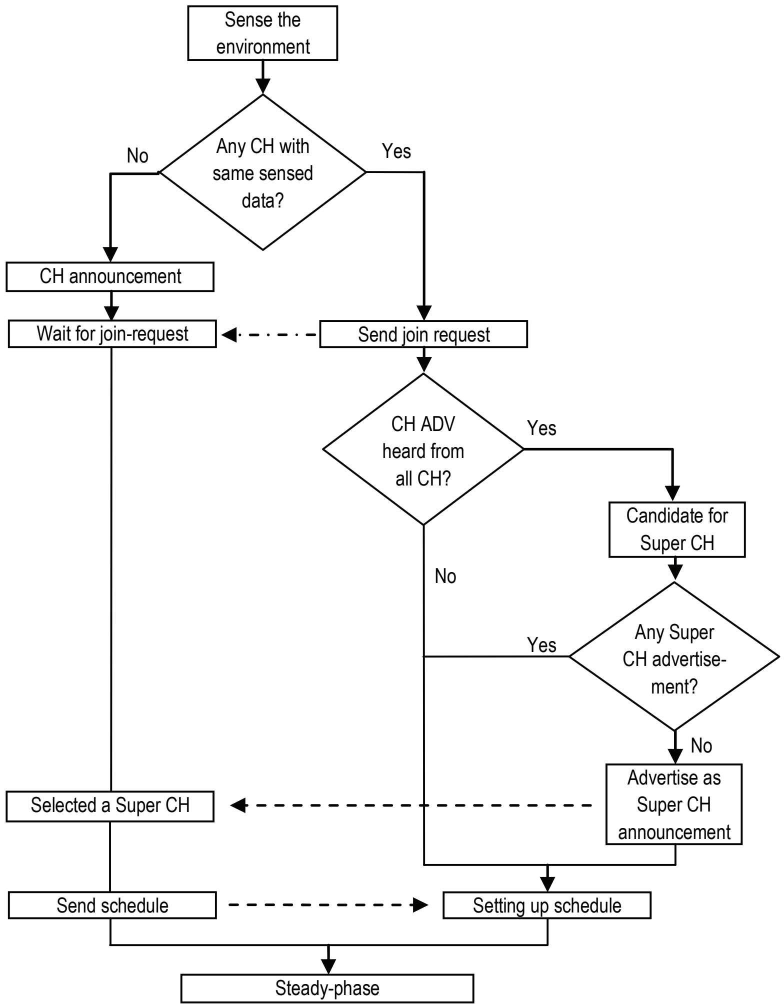

Fig. 2. Distributed formation and operations of sensor nodes

- Step 3: By the previous step, the cluster heads are already hooked up with a single super cluster head. Now the cluster heads proceed with creating TDMA schedules. Schedules for each cluster contain specific slot time for every member nodes. The schedules are sent to the members in an unidirectional manner. Thus, for the current round, every node is aware of its slot time.
- Step 4: Now, the nodes enter into the steady phase. Each member node sends its sensed data to the cluster head. At the end of the frame time, the cluster head aggregates the received data and determined the shorter distance from itself to the super cluster head and to the base station. If the base station is nearer, it sends the aggregated packet directly to the base station. In the other case, the cluster heads send its aggregated data packet to the super cluster head.
- Step 5: The super cluster head waits for the cluster head packets for a certain period till the frame time. This period is determined by duration between the first and last advertisement message

heard by the super cluster head during step 2. After this duration, the super cluster head aggregates the received packets and sends to the base station.

In the consecutive rounds, the steps 1 to 5 are executed repeatedly. In Fig. 2, these steps are shown in a flow chart. However, there are a number of essential factors to be taken into account. These factors greatly affect the overall performance of the protocol. These factors are mentioned below according to their role.

- Member node: In consecutive rounds, after sensing the context of the environment, a node compares the current context with the previous one. If it is the same, the node does not send any packet. For this purpose, nodes always temporarily store their sensed data for a single round.

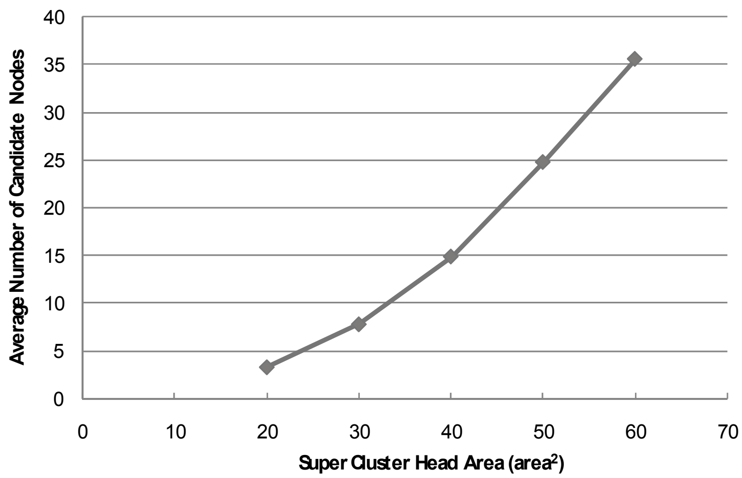

Fig. 3. Average number of candidate nodes

- Cluster head: If a cluster head has not received data from a node within the specified time slot, the cluster head considers that slot as blank and send as it is in the aggregated packet to the super cluster head. The second consideration is while declaring itself as a cluster head, a node checks its role history whether it has become cluster head in previous rounds or not. If so, it restrains itself in becoming a cluster head. To maintain such facility, the cluster head checks the role history of every member node upon forming a cluster. If all member nodes have become cluster heads in previous rounds, an appropriate flag is sent to every node with the schedule message to erase their role history. Thus, from the next round, every node is eligible to become a cluster head satisfying the perquisites. This actually ensures the uniform distribution of the cluster head role which is responsible for equal energy dissipation across the network.
- Super cluster head: Before declaring itself as a super cluster head, a node checks its role history for the number of rounds ago it has played such role. This means that, a node cannot play such role consecutively. This number of rounds depends on the number of candidate nodes within the super cluster area. Through extensive simulation, the average number of candidate nodes for different super cluster area has been investigated. The result is shown in Fig. 3 which

exhibits that for a super cluster area of 20x20, the average number of candidate nodes is around 4. As this area is further expanded, the number of candidate nodes also increases. Keeping a safety margin, the number of candidate nodes can be considered as 6 for a 30x30 area (Area selection has been explained in next section). Thus, a node can be a super cluster head again after 6 rounds. This actually ensures super cluster head role rotation to a considerable extent.

- Base station: Base station is considered as having far greater storage and computational ability. When an aggregated packet is received, it is extracted and the content is stored according to the corresponding slot. When a certain slot is found blank, it assumes that the data is same as before and the base station proceeds with the previous data for that slot. This technique in fact reduces considerable amount of traffic and contributes in energy efficiency.

In LEACH protocol [6], communication interference has been minimized by using different CDMA codes for each cluster. Each cluster head selects a different CDMA code and informs its member nodes. Our proposal adopts this technique which efficiently filters the neighbor's signal and eliminates the possibility of corrupt signal.

4 Performance Evaluation

The performance of CAMHP has been evaluated in a simulation environment where the temperature of the surrounding was monitored. Such an environment was created on the sensor network extension of J-Sim [14]. J-Sim has been selected here for its simple component-based software architecture and better debugging capability. However, it is quite difficult to find another context-aware hierarchical protocol with much referred performance. Thus, we had selected LEACH protocol [6] and a simple Multi-Hop model for the performance comparison which have been treated as the benchmark in many related publications. As energy efficiency is one of our key objectives, energy consumption and node's operating duration was meticulously measured and analyzed.

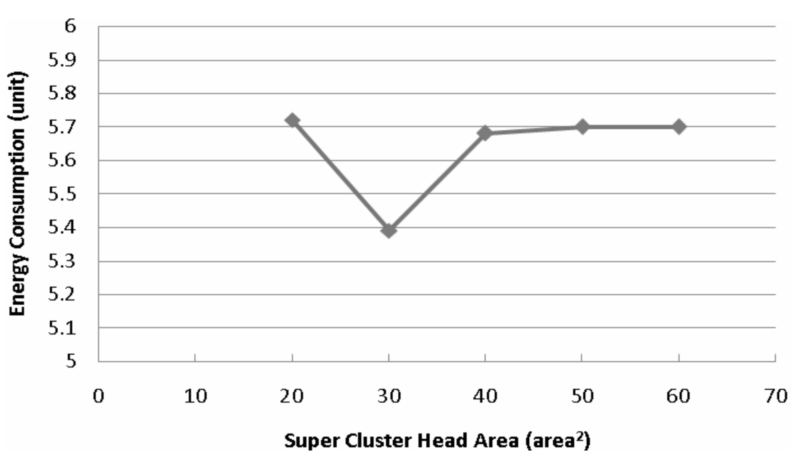

Fig. 4. Energy consumption for different super cluster area

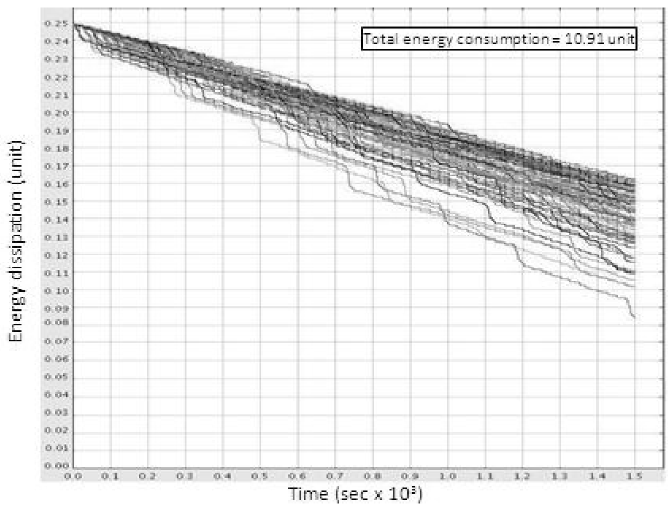

Fig. 5. Energy dissipation in CAMHP

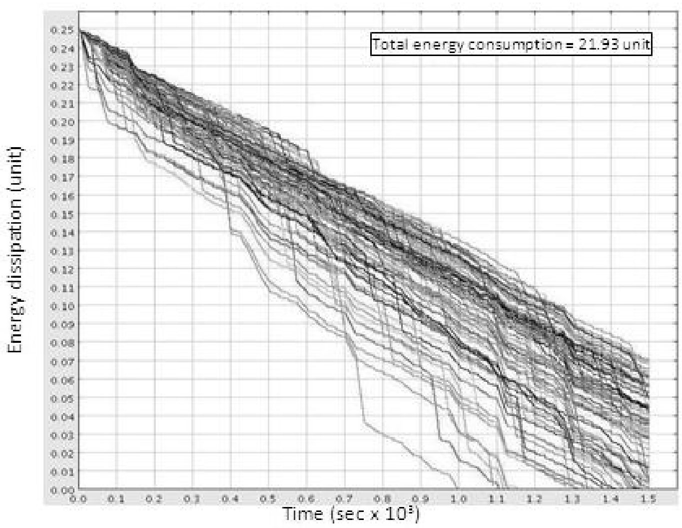

Fig. 6. Energy dissipation in LEACH

4.1 Radio and Network Model

We used the radio and network models that were quite similar to the models of LEACH protocol simulation. An environment was created where the temperature of the environment was different in four regions of the area and was changing continuously. Total 100 sensor nodes were deployed in this 100x100 area in a random manner. All the nodes were symmetric and initially had 0.25 unit energy. To get the network's energy consumption trend faster, the nodes were given less energy.

The radio model was quite simple. Nodes were simulated with 914 megahertz frequency and had maximum bandwidth of 1 megabyte. Energy consumption of each node was calculated using Friss equation [4] based on the distance between transmitter and receiver. The base station was located in (0,0) location which was one corner of the area. The most important difference with the LEACH simulation was that LEACH nodes were able to communicate from any corner of the simulation area to the base station. In real world scenario, this is relatively impractical for such limited communication capable nodes. In our simulation, nodes are set with maximum communication range of 70 in the 100x100 area. Thus, nodes had to communicate with the base station through the clustering hierarchy. To find the appropriate super cluster area, transmission energy consumption is measured for different super cluster area ranging from 20x20 to 60x60. As shown in Fig. 4, if the super cluster area is 30x30, transmission energy consumption is the lowest. Therefore, super cluster area is set as 30x30 in the middle of the total area. From this region, candidate nodes were able to hear advertisement from all the cluster heads.

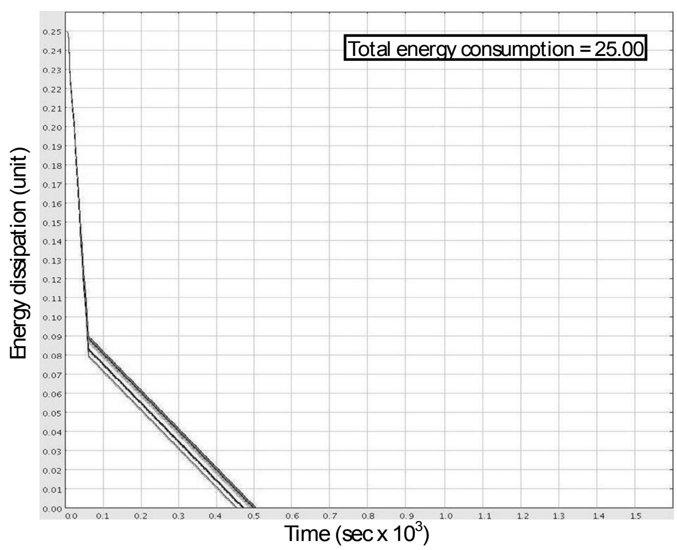

Fig. 7. Energy dissipation in Multi-Hop model

4.2 Simulation Results

The energy dissipation of CAMHP is shown in the Fig. 5. The duration of the simulation was 1500 seconds. At the end of the simulation, all nodes of the network were fully active and having an approximate average energy of 0.13 unit. The total energy consumption of the network was 10.91 units. The performance of LEACH is shown in the Fig. 6. With the same duration, a number of nodes were out of service and the average remaining energy became just over 0.02 unit. Furthermore, the total energy consumption of the network was 21.93 units. However, energy dissipation rate of the

Multi-Hop model was quite disastrous as shown in Fig. 7. All the nodes were out of service at around 510th seconds. Nodes were set to send own data until energy reach 0.09 unit and after that, the remaining energy was used to finish off the queue. In the Fig. 8, a comparison between CAMHP, LEACH and Multi-Hop model is shown for numbers of nodes remaining alive. For CAMHP, all the 100 nodes were alive. However, for LEACH, the first node was out of service in around 1000th second and at around 1500th second, 24 nodes were completely out of service. Thus, almost three-fourth of nodes was remaining alive. And, in multi-Hop model, within 450th and 510th seconds nodes were dead. Table 1 shows the number of packets sent and dropped by LEACH, CAMHP and Multi-Hop model. Within the simulation period, only 3 packets were dropped in CAMHP.

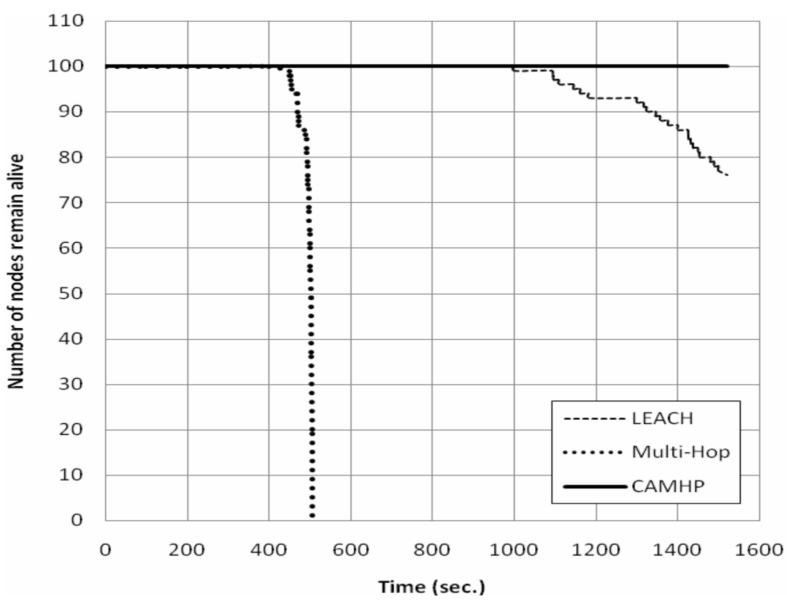

Fig. 8. Sensors remaining alive in LEACH, Multi-Hop model and CAMHP

Table1. Total number of packets sent and dropped in LEACH, CAMHP and Multi-Hop model

	LEACH	*CAMHP*	*Multi-Hop*
Total packets sent	62407	16614	572
Total packets dropped	169	3	79

4.3 Analysis and Discussions

Energy efficiency is one of our key objectives in CAMHP. Comparing the Fig. 5, 6 and 7, CAMHP consumed half of the total energy consumed by LEACH and far less energy compared to Multi-Hop model. As a result of such energy consumption, all the sensor nodes were fully active at the end of the simulation. Whereas, 24 nodes were out of service in LEACH at the end of the simulation and remaining sensors were presumed to be operational until around 2300^{th} second. And, in Multi-Hop model, none of nodes were alive after 510^{th} seconds. As the Fig. 5 shows, the pattern of energy consumption of nodes is quite symmetric in CAMHP. This is actually a result of uniform cluster head role rotation and near optimal super cluster head role rotation techniques. In the counterparts, LEACH shows a discrete pattern and Multi-Hop model shows rather drastic pattern for energy consumption of the nodes. Table 1 depicts that LEACH has sent almost 4 times more packets to the base station than CAMHP. Moreover, the number of packets dropped in LEACH is 56 times more than in CAMHP. The exemption in sending same context packets has reduced the data traffic in CAMHP to a great extent. This technique also has decreased the number of dropped packets in CAMHP. In Multi-Hop, although the numbers of sent packets are quite low, the numbers of dropped packets are far higher than CAMHP. Altogether, CAMHP has outperformed both LEACH and Multi-Hop model in case of energy efficiency, operational duration and accurate data traffic. Moreover, CAMHP has the capability to cover more area than LEACH through its multilayer hierarchy.

5 Conclusion and Future Works

In this paper, a context-aware cluster based hierarchical protocol is proposed which aims to maximize the energy efficiency in WSN. This three layered hierarchical protocol forms the clusters in the first layer based on the context of the environment. In that layer, the cluster head of a cluster is selected based the previous role history so that, the cluster head role can be uniformly distributed among the member nodes of that cluster. On the second layer, the super cluster head is selected from a set of candidate nodes complying with near optimal role rotation technique. Thus, energy consumption of the total network is shared among the nodes ensuring longer active service. Moreover, member nodes refrain themselves in transmitting packets with the same content as previous iteration. This technique reduces data traffic to a great extent. The three layered hierarchical structure is capable to cover more ground where sensor nodes have limited communication range. Performance evaluation of CAMHP shows significant energy efficiency compared to LEACH and Multi-Hop model. As a whole, techniques applied in CAMHP perform efficiently in energy saving and the network provides a longer full-scale active service.

The future work of this protocol includes finding a more sophisticated super cluster head role rotation technique which will improve the overall performance by ensuring maximum utilization of the candidate nodes. Again, an elegant procedure can be pursued to handle the degradation of node's communication capabilities at the ending phase of network life. Moreover, as sensor applications are now dealing with wider WSN area, CAMHP might be tested with a large number of nodes with sufficient simulation resources.

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