# Base Station Controlled Adaptive Clustering for Qos in Wireless Sensor Networks

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**Summary**
Wireless Sensor Networks (WSNs) are a collection of nodes organized into a cooperative network. Harsh and dynamic physical environments and extremely limited resources are major obstacles for satisfying QoS metrics. This paper proposes and analyzes an Base station Controlled Adaptive Clustering Protocol (BCACP) for Wireless Sensor Networks suitable to support real time traffic. The protocol achieves fault tolerance and energy efficiency through a dual cluster head mechanism and guarantees the desired QoS by including delay and bandwidth parameters in the route selection process. Simulation results indicate that BCACP reduces overall energy consumption and improves network lifetime while maintaining required QoS.
***Key words:***
*Clustering, energy efficiency, fault tolerance, Packet Delivery Ratio (PDR), Quality-of-Service (QoS), Wireless Sensor Networks (WSNs)*

## 1. Introduction

Wireless Sensor Networks (WSNs) can be defined as the representative non-infrastructure networks that are capable of wireless communication. WSNs are composed of a large number of sensors which are intelligent, miniaturized and lightweight, having limited computational, sensing capability, memory size, radio transmission range and energy supply. Sensors are spread in an environment and cooperate to accomplish common monitoring tasks like sensing environmental data. With WSNs, it is possible to assimilate a variety of physical and environmental information in near real time from inaccessible and hostile locations.

WSNs have a wide variety of applications in home security, battle field surveillance, target tracking, industrial process monitoring, environment monitoring and health care applications. WSNs are extensively used in hazardous and inaccessible locations inside a chemical plant or nuclear reactor and aid in minimizing the risk to human life. WSNs are being rapidly deployed in patient health monitoring in a hospital environment, where different health parameters are obtained and forwarded to health care servers accessible by medical staff also surgical implants of sensors can help monitor a patient's health.

Emerging WSNs have QoS requirements that include fault tolerance, timeliness and reliability. The timeliness and reliability level for data exchanged between sensors and base station is of paramount importance especially in real time scenarios. Thus QoS routing is an important topic in sensor networks research, hence there is a growing interest in the literature on proposals for QoS routing in WSNs. In order to satisfy the QoS requirements and energy constraints for WSNs, hierarchical (clustering) techniques have been an attractive approach to organize sensor networks based on their power levels and proximity. In each cluster, sensor nodes are delegated different roles, such as cluster head or ordinary member node.

A cluster head (CH) is elected in each cluster that collects sensed data from member nodes, aggregates and transmits the aggregated data to the next cluster head or to the base station (BS). The role of ordinary member node is to sense data from the environment and communicates the data to the cluster head.

**Motivation**: The cluster based network model provides inherent optimization capabilities at cluster heads, such as data fusion and reduces communication interference by using TDMA (Time Division Multiple Access). High energy nodes can be used to process and send the information while low energy nodes can be used to perform the sensing task. Overall, clustering is an excellent approach for achieving scalability, lifetime, energy efficiency, and reduce network contention. While earlier works (explained in the Section 2) were primarily focused on the above mentioned aspects, more recent research have begun to consider fault tolerance, reliability, and quality-of-service and our proposed protocol is motivated by these metrics.

**Contribution**: This proposed protocol Base Station Controlled Adaptive Clustering Protocol (BCACP) employs a fault tolerant dual cluster head mechanism in the cluster with respect to the working of the cluster head and guarantees the desired QoS by including delay and bandwidth parameters in the route selection process. Furthermore, the protocol evenly distributes the energy consumption to all nodes so as to extend the sensor network lifetime. We test the performance of our proposed approaches by implementing our algorithms using ns-2

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simulator. Our results demonstrate the performance and benefits of our algorithm. The rest of the paper is organized as follows: Section 2 gives a review of Related Works. Section 3 and Section 4 explains the Problem, Network Model, notations and assumptions. The algorithm is explained in Section 5. The Simulation and Evaluation of the algorithm is presented in Section 6. Conclusions are presented in Section 7.

## 2. Related Work

In this section a summary of the current state-of-the-art in hierarchical routing protocols for WSNs are presented with the highlights of the performance issues and limitations of each strategy. Low-Energy Adaptive Clustering Hierarchy (LEACH) [1] is a self-organizing, adaptive clustering based protocol that uses randomized rotation of cluster heads to uniformly distribute the energy load among the sensor nodes in the network. The cluster heads have the responsibility of collecting data from their clusters, and fuse the collected data for reducing the amount of messages to be sent to the Base Station, which results in less energy consumption. The broadcast messages as well as cluster formation messages are transmitted using CSMA (Carrier Sense Multiple Access) to minimize collisions. Following cluster establishment, cluster heads will generate a transmission schedule and broadcast the schedule to all the nodes in their respective cluster. The schedule consists of TDMA slots for each neighboring node. This scheduling scheme allows for energy minimization as nodes can turn off their radio during all but their scheduled time slot. In the centralized version of this protocol, LEACH-C [2], the base station handles the clustering procedure. Despite these benefits, LEACH and LEACH-C suffer several shortcomings. Cluster head selection based on probability will not automatically lead to minimum energy consumption. Cluster head route messages to the Base Station in a single hop, when the network size grows, it is possible that these cluster heads will discharge faster than others and if the distance is large the messages may not reach the Base Station.

Threshold sensitive Energy Efficient sensor Network (TEEN) [3] and its adaptive version (AdaPtive) Threshold sensitive Energy Efficient sensor Network (APTEEN) [4] are clustering protocols that are comparable to LEACH, they are sensitive to sudden changes in WSNs. Both the protocols designate the transmitting nodes by using threshold mechanisms. The drawbacks of the two approaches are the overhead associated with forming clusters at multiple levels and the method of implementing threshold based functions.

Lindsey and Ragavendra proposed a near optimal chain-based protocol called Power Efficient Gathering in Sensor Information Systems (PEGASIS) [5]. Rather than classifying nodes into clusters, the algorithm forms chain of sensor nodes. Based on this structure, each node transmits to and receives from only closest nodes of its neighbors. The node performing data aggregation forwards the data to the node that directly communicates with the sink. In each round, a greedy algorithm is used to elect one node in the chain to communicate with the sink. The weaknesses of the protocol lies in the fact that the single leader can itself become a bottleneck in the network. Akkaya and Younis [6] proposed a cluster based QoS aware routing protocol that employs a queuing model to handle both real-time and non real time traffic. The protocol only considers the end-to-end delay. Furthermore, the transmission delay is not considered in the estimation of the end-to-end delay, which sometimes results in selecting routes that do not meet the required end-to-end delay.

Younis et al., [7] presented a new clustering model called HEED (Hybrid Energy-Efficient Distributed clustering), in which cluster heads are elected through finite iteration, taking into account nodal residual energy and the inner cluster's communication costs. The quality of clustering in HEED is better than LEACH, but requires higher communication costs, and the time synchronization difference is relatively large.

Stable Election Protocol [8] uses a non-homogeneous sensor nodes to distribute energy uniformly in WSNs. The method of cluster head selection is based on two different levels of energy. A node with the highest weight according to their different energy is elected as cluster head. Subsequent cluster heads are elected using this process. This approach ensures that cluster heads are randomly selected and energy consumption is uniformly distributed among sensor nodes.

Two-Level Hierarchy LEACH (TL-LEACH) [9] algorithm elects two sensor nodes in each cluster as cluster heads, one node as primary cluster head and the other as the secondary cluster head. Both the primary and secondary cluster heads can communicate with each other and secondary cluster heads communicate with nodes in their sub-clusters. The two-level structure of TL-LEACH reduces the amount of nodes that need to transmit to the base station, effectively reducing the total energy usage. However, there is a high probability of increase in overhead during the selection of primary and secondary cluster heads which results in higher energy consumption. Chen et al., [10] developed a local centralized method for electing a dual cluster head and introduce a parameter to measure the QoS support in hierarchical applications of WSNs. The protocol can increase the reliability and the steadiness of wireless sensor network by distributing evenly the communication load and the load of data fusion among cluster-heads. The dual cluster head model can also improve the survival ability of wireless sensor networks. The shortcoming of the protocol is that the secondary cluster is created only if the number of nodes in a given cluster is greater than a threshold; the protocol proposed in this paper always creates a secondary cluster to achieve fault tolerance in the WSN.

Muruganathan et al., [11] proposed a Base-Station Controlled Dynamic Clustering Protocol (BCDCP), which utilizes the high-energy base station to perform most energy intensive tasks and distributes the energy dissipation evenly among all sensor nodes to improve network lifetime and average energy savings. BCDCP relies on the base station to perform balanced cluster formation, path selection and other energy intensive tasks. Multi-hop communication among cluster heads is employed to reach the base station, through the lowest energy path.

Haiping and Ruchuan [12] propose a novel clustered control algorithm based on location information, energy, priority of coverage and multi-layered architecture This approach selects a cluster-head according to geographical locations and residual energy at the nodes and ensures the higher coverage rate for the cluster head by a priority mechanism to avoid the concentrated and marginal distribution of cluster-heads. This approach reduces the energy cost by increasing the sleeping nodes during non-media data transmission phase and adding many intermediate nodes to forward data during multimedia media data transmission which in turn prolongs the lifetime of the network.

Peng et al., [13] propose a protocol that focuses on improving the energy efficiency and other QoS parameters by excluding the node with improper geographic location to be the cluster heads. Feng et al., [14] design a High Available Sensor network protocol for Differentiated Services (HADS), which computes the routing gradient with different metrics, and then constructs two types of routing gradient table for best-effort service and real-time service.

Hossein et al., [15] use cluster heads as higher power relay nodes in a two-tiered WSN and these relay nodes may form a network among themselves to route data towards the sink and provide energy efficient QoS routing in cluster based WSNs. Ben-othman et al., [16] develop a protocol that provides Quality of Service (QoS) by employing a queuing model to classify the traffic depending on its importance into four different queues. Higher priority queues have absolute preferential treatment over low priority queues. Aslam et al., [17] use Network Calculus to present a mathematical model of a TDMA-based medium access control protocol, where a cluster based system is modeled and arrival/service curve is proposed. In addition, the model is also extended to allow finding the maximum delay and backlog bounds for applications with certain QoS requirements.

Dehnavi et al., [18] propose a QoS routing protocol that performs cluster heads election and route discovery using multiple criteria such as residual energy, remaining buffer size, signal-to-noise ratio and distance to sink. The protocol maximizes the network lifetime through data transmission across multiple paths as load balancing that causes energy consume uniformly throughout the network. Furthermore employs a queuing model to handle both real-time and non-real-time traffic.

Fapojuwo et al., [19] designed a Quality of service enhanced Base station Controlled Dynamic Clustering Protocol (QBCDCP). The protocol achieves energy efficiency through a rotating head clustering mechanism and delegation of energy intensive tasks to a single high power base station, while providing quality of service support by including delay and bandwidth parameters in the route selection process. In the proposed protocol we employ a dual cluster head model to attain fault tolerance and improve the lifetime of the WSN, also the dual cluster head model aids in enhancing the end-to-end delay and packet delivery ratio (PDR).

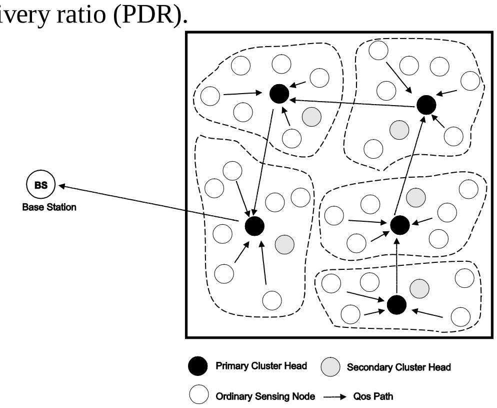


Fig. 1 Network Model

## 3. Problem Definition

The topology of a wireless sensor network may be described by a graph *G=(N,L)*, where, *N* is the set of nodes and *L* is the set of links. The objectives are to:

(i) Improve the lifetime of the sensor network.

(ii) Reduce the average end-to-end packet delay.

(iii) Minimize the packet delivery ratio (PDR).

## 4. System Model

In our system model, we assume the following:

(i) The wireless sensor network consists of N homogeneous sensor nodes, deployed at random locations in a sensor field. An example scenario is shown in Fig. 1 where, the sensor field is a square area at a distance $d_{BS}$ from a single fixed base-station. The sensors are grouped into 1-hop clusters with a specific clustering algorithm. All sensor nodes are immobile.

(ii) All the nodes in the network start with the same initial energy and are battery power, processing power and memory space constrained.

(iii) The N sensor nodes are powered by a non renewable on board energy source. When this energy supply is exhausted, the sensor becomes non-operational. All nodes are supposed to be aware of their residual energy and are capable of measuring the signal strength indicator (RSSI) of a received message; this measurement may be used as an indication of distance from the sender.

(iv) The nodes in a cluster may perform either of three roles: primary cluster head, secondary cluster head or sensing. Each cluster head performs activities such as scheduling of intra-cluster and inter-cluster communications, data aggregation and data forwarding to the base station through multi-hop routing. The role of the secondary cluster head is to emulate the role of the role of the primary cluster head in case of its failure. On the other hand, a sensing node may be actively sensing the target area.

(v) The information sensed by the sensing nodes in a cluster are transmitted directly to their cluster head.

(vi) The cluster head, gathers data from the other nodes within its cluster, performs data aggregation/fusion, and routes the data to the base station through other cluster head nodes. The base station in turn performs the key tasks of cluster formation, cluster head selection, and cluster head to cluster head QoS routing path construction.

(vii) The base station has knowledge via internal global positioning system (GPS) of the position of all nodes inside the sensor field. The base station has a constant power supply and thus, has no energy constraints. Hence, it can also be used to perform functions that are energy intensive and can also hold past data. The base station can transmit directly to the nodes, however the nodes due to their limited power supply may not be able to communicate with the base station directly, except the nodes close to the base station.

(viii) Radio Model : The energy required at the transmitter amplifier to guarantee an acceptable signal level at the receiver, when receiver and transmitter are separated by a distance d, $E_a(d)$ is:

$$E_a(d) = \begin{cases} \epsilon_{FS} d^2, d \leq d_o \\ \epsilon_{TR}\, d^4, d \geq d_o \end{cases} \quad (1)$$

where, $\varepsilon_{FS}d^2$ and $\varepsilon_{FS}d^4$ denote the transmit amplification parameters corresponding to the free-space and two-ray models, respectively, and do is the threshold distance given by:

$$d_o = \sqrt{\frac{\epsilon_{FS}}{\epsilon_{TR}}} \quad (2)$$

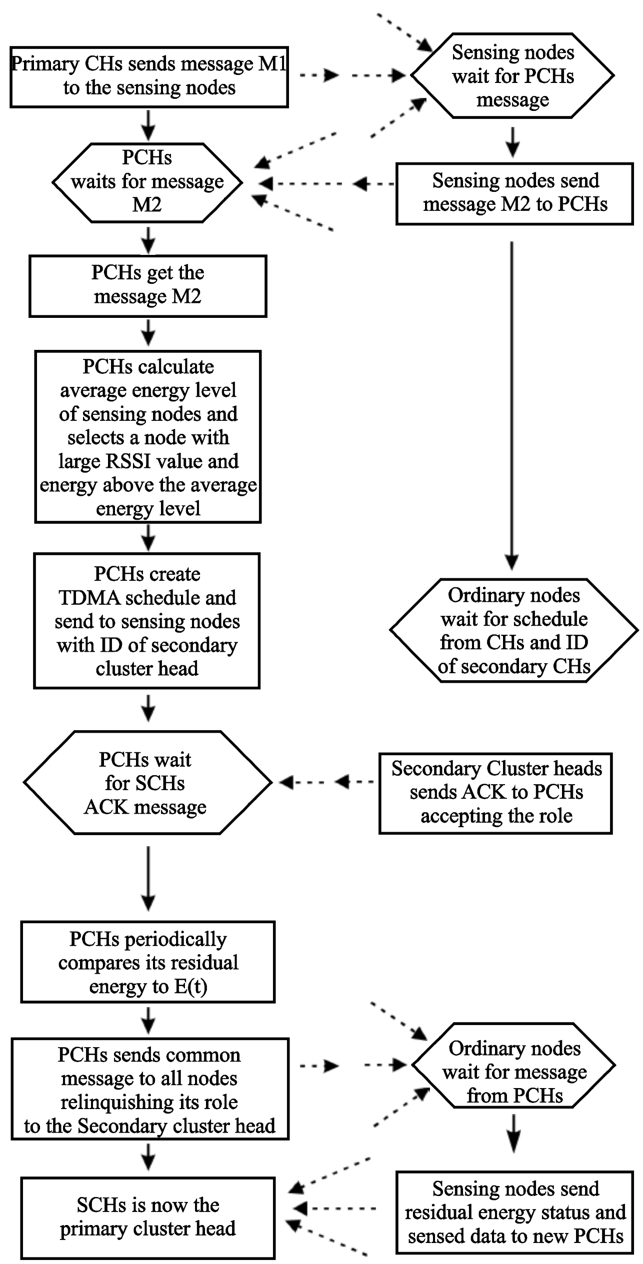


Fig. 2 Selection of Secondary Cluster Head

## 5. Algorithm

The proposed protocol BCACP incorporates QoS requirements like fault tolerance, delay and bandwidth information during route establishment. The energy intensive tasks are delegated to the base station to improve the lifetime of the network. The operation of the protocol is split into phases. The first stage of BCACP consists of the cluster splitting and primary cluster selection the second phase involves the selection of secondary cluster head. The last phase involves formation of the QoS route from cluster head to the base station. TDMA (Time Division Multi Access) and spreading code are engaged to minimize inter-cluster interference to allow simultaneous transmissions in neighboring clusters.

### 5.1 Cluster Setup and Primary Cluster Head Selection:

In the proposed protocol the cluster splitting and primary cluster head selection is accomplished by the Base Station [11] as shown in Phase I of Algorithm 1.

### 5.2 Secondary Cluster Head Selection

In the next phase the primary cluster head has the role of identifying the secondary cluster head, the steps involved are shown below and illustrated in Fig. 2.

(i) Each new primary cluster head sends message $M_1$ to the sensing-nodes in the cluster, the message contains the node's ID and a header to distinguish the message.

(ii) The sensing-nodes record the Received Signal Strength Indicator (RSSI) of message $M_1$. The sensing-nodes nodes send message $M_2$ to the primary cluster. The message contains the node's ID, ID code of the primary cluster head, RSSI value of message received from the primary cluster head and the current residual energy of the node.

(iii) The primary cluster head receives $M_2$ from ordinary nodes, the cluster head calculates the average residual energy level of all sensing-nodes in the cluster. It selects a secondary cluster from one of the nodes which has the largest RSSI of message $M_1$ among the qualified nodes whose residual energy is more than the average residual energy of all nodes in the cluster.

(iv) The primary cluster head sets up TDMA schedule and transmits the schedule to the secondary cluster head and the sensing-nodes in the cluster. The role of the secondary cluster head is to emulate the primary cluster head in case of its failure.

(v) The primary cluster head sends a message $M_3$ periodically to the secondary cluster head informing its role and its current residual energy status. The secondary cluster head sends a ACK back to the primary cluster head on receiving the message.

(vi) When the residual energy of the primary cluster head is equal to or less than the $E_t$ (threshold energy level) the primary cluster head relinquishes its role to the secondary cluster head by sending a common message to all nodes in cluster.

(vii) The new primary cluster updates the base station of its delay, bandwidth and residual energy of the sensing nodes, it continues the functions of the cluster head using the same TDMA schedule.

(viii) In The base station triggers re-clustering process only when more than 25% of secondary cluster heads have reached their $E_t$, also it assigns the new $E_t$ level for the next round based on the average residual energy of selected primary cluster heads. This process prevents frequent re-clustering and avoids excessive depletion of the cluster heads battery, this mechanism results in better power efficiency.

### 5.3 QoS Route Establishment

The desired QoS metrics for route establishment i.e., delay, bandwidth of cluster head nodes and residual energy of the sensing nodes are aggregated and reported to the base station periodically. Delay and bandwidth are measured at cluster head nodes. The delay associated to traversing a particular cluster head is, the time duration between entering the input queue and leaving the output queue of the cluster head $D_{xy}$. Bandwidth is computed at each cluster head as the number of free time slots within each cluster head $Bw_{xy}$.

When a connection is desired, the base station sets up a QoS-based route $Q_S$ between the cluster head where the connection is initiated and itself as shown in Fig. 1. The base station finds the route which minimizes the delays and power amplifier energy along the path, and has a minimum bandwidth greater than or equal to the requested bandwidth $BW_{req}$ as shown in Algorithm 1. The algorithm may produce more than one optimal path, the path having cluster heads with minimum power amplifier energy $E_{aSum}$ is chosen. After a route is chosen, the base station communicates it to the concerned cluster head nodes, which schedule the connection by specifying the required number of time slots to maintain it. During the communication phase when the primary cluster head is depleted of energy it transfers its role to the secondary cluster head. But, the primary cluster head is currently involved in the QoS path hence it informs both the downstream cluster head, upstream cluster head and the base station of its duty transfer and then relinquishes its role. The traffic is redirected to the new primary cluster and the QoS level is maintained throughout the duration of the connection.

**Phase I** : Cluster Setup and Primary Cluster Head Selection
**Input :** *N* Nodes, \$$E_c$ Current energy level at each node
**Output :** Balanced clusters and Primary Cluster Heads
Calculate the average residual energy level of all the nodes
**Repeat** (*N* clusters with primary cluster heads have been selected)
{
(1) From set of nodes in *N*, choose two nodes $ch_1$ and $ch_2$ that have maximum separation distance between them;
(2) Assign the remaining nodes to the closest cluster head $ch_1$ or $ch_2$, whichever being closer to from two clusters;
(3) Balance the two clusters so that they have approximately the same number of nodes;

(4) Split *S* into smaller sets $s_1$ and $s_2$ whose elements are the group members in step 3
}
**Return** *N* clusters, Primary cluster heads;

**Phase II** : Secondary Cluster Head Selection
**Input:** *N* clusters, Primary cluster heads;
**Output:** Secondary Cluster Heads;
Secondary Cluster Head Selection: 5.2;
**Return** Secondary Cluster Heads;

**Phase III :** QoS Route Establishment
**Input:** *C* is the set of primary cluster heads (PCHID);
DPCHID (Destination Primary Cluster Head ID), $BW_{req}$(Minimum bandwidth required), $D_{req}$(End-to-end delay required), $BW_{xy}$(Bandwith offered by link xy), $D_{xy}$(Delay associated with link xy), $E_a(d_{xy})$(Power Amplifier energy of current cluster head, which is a function of the distance between the cluster heads and radio propagation model)
**Output:**Optimal QoS Path from Base Station to requesting Primary Cluster Head

```
For each PCHID in C{
    If(Bxy ≥ BW_req){
        D_Sum = D_Sum+D_xy;
        E_aSum = E_aSum+E_a(d_xy);
        Add PCHID to R;
        If(PCHID == DPCHID){
            If(D_Sum ≤ D_req){
                Add the path R and E_aSum of path to Q_R;
            }
            Else{Discard R;
        }
    }
    Else{
        continue;
    }
}
Else{Discard R;}
For each R in Q_R{
    Return Q_S with Min E_aSum}
Return Q_S;
```

Algorithm. 1 Base Station Controlled Adaptive Clustering Protocol

## 6. Performance Evaluation

To evaluate the proposed protocol, we carried out a simulation study using ns-2 [20] a discrete event simulator. The proposed protocol BCACP is compared with QBCDCP. The simulation configuration consists of 100 nodes where each node is assigned an initial energy of 2 Joules, located in a 100 $m^2$ area. The base station is located 25m from the sensor field. The end-to-end delay objective $D_{req}$ is fixed at 10seconds and $BW_{req}$ was set at 16 Kbps by assigning each connection one out of 16 available TDMA time slots. Table 1 summarizes the simulation parameters.

Table 1: Simulation Parameters.

| Simulation Parameters | Values |
|---|---|
| Number of Sensors | 100 |
| Simulation Topology | 100mx100m |
| Distance to Base Station | 25m |
| Cluster radius | 30m |
| Threshold Distance ($d_o$) | 75m |
| Data Packet Size | 300 bytes |
| Control Packet Size | 25 bytes |
| Initial Energy | 2.0 Joules |
| Energy spent for Send/Receive | 50nJ/bit |
| Energy spent for data aggregation | 5nJ/bit |
| Free Space Model Parameter | 10pJ/bit/$m^2$ |
| Two-Ray Model Parameter | 0.0013pJ/bit/$m^2$ |

A comparison of the average residual energy of cluster heads, average end-to-end delay and packet delivery ratio (PDR) for different loads are obtained. Fig. 3 illustrates the role of the secondary cluster head in increasing the overall lifetime of the sensor network. In QBCDCP during the communication phase if the primary cluster head is depleted of energy, the entire cluster does not function and causes the WSN to become unstable and inconsistent. This problem can be overcome by the dual cluster head model. In BCACP the cluster will continue to work reliability since the secondary cluster head takes the role of the primary cluster head when the threshold ($E_t$) energy is reached. In QBCDCP the cluster formation is triggered frequently since the cluster head gets depleted of energy quickly.

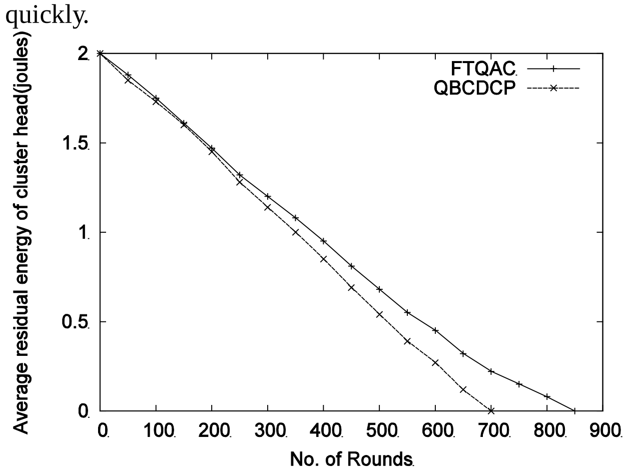


Fig. 3 No. of Rounds Vs. Average Residual Energy of Cluster.

In Fig 3 the characteristics of both the protocols are similar initially since the energy level of the cluster heads are high, but during the later stage of simulation the average residual energy of primary cluster head in BCACP is higher since the primary cluster head relinquishes its role to the secondary cluster head. This model of dual cluster head has the feature of fault-tolerance and improves the robustness of the WSN. From Fig. 4 it is observed that there is about 15% increase in the network lifetime using the dual cluster head model.
Fig. 3 shows the average end-to-end delay for BCACP and QBCDCP. In this evaluation we change the packet arrival rate at the source node and measure the end-to-delay. As

expected, the increase in network load produces a higher queuing delay at each cluster head along a path, which gives a larger end-to-end delay. At a packet rate of 60 packets per second QBCDCP is unable to meet the delay objective of 10 seconds, due to the rapid depletion of energy in the cluster head, network congestion will emerge at the cluster head because of limited energy and computing ability. The base station sets up paths based on the power amplifier energy of the cluster heads, hence if a cluster head with low residual energy is selected for the QoS path, this will result in drop of the link during the communication phase and effect the desired QoS. In BCACP the dual cluster head model will ensure the necessary energy level and bandwidth required for maintaining the link from base station to requesting cluster head node.

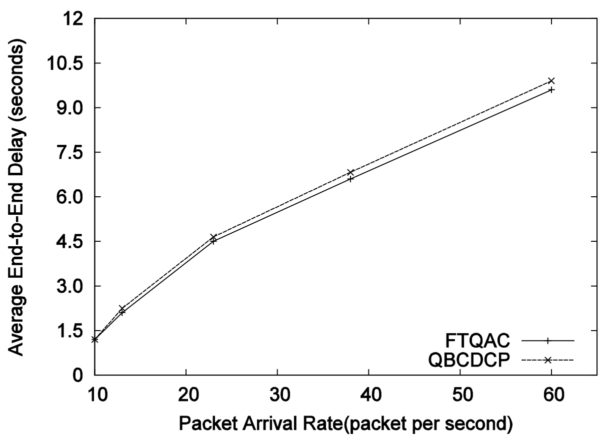


Fig. 4 Packet Arrival Rate Vs. Average End-to-End Delay

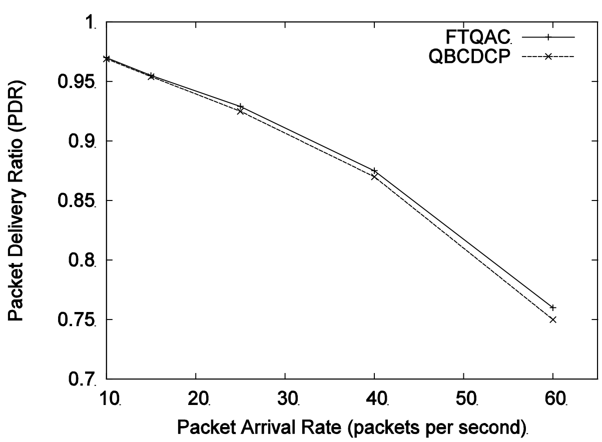


Fig. 5 Packet Arrival Rate Vs. Packet Deliver Ratio.

As depicted in Fig. 5 the packet delivery ratio (PDR), decreases as the packet arrival rate increases. The packet delivery ratio is defined as the number of packets generated by the source to the number of packets received by the destination node. It is observed that BCACP performs marginally better than QBCDCP when the packet arrival rate is above 30 packets per second. In QBCDCP as the packet arrival rate increases the cluster head in the QoS path will get depleted of energy and the connection will be terminated, triggering route repair and hence result in a lower PDR. In BCACP the role transfer from primary cluster head to secondary cluster head will ensure that the scheduled connection will not be dropped hence maintaining the packet delivery ratio.

## 7. Conclusion

The Base station Controlled Adaptive Clustering Protocol proposed in this paper achieves QoS routing in wireless sensor networks by using delay and transmission energy as the routing metrics. It also ensures that the bandwidth objective of the application is met. The protocol achieves fault tolerance through a dual cluster head mechanism and guarantees the desired QoS. The performance of BCACP was evaluated through simulation techniques and the results show an increase in lifetime of the WSN. The BCACP provides an improvement of up to 15% in lifetime over QBCDCP, while obtaining similar end-to-end delay objective over different loads. The BCACP is a feasible solution to the QoS routing problem in power constrained wireless sensor networks.

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