CA-RPL: A Clustered Additive Approach in RPL for IoT Based Scalable Networks

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Abstract. Applications of the Internet of Things (IoT) span from the industrial field to the agriculture field and from the smart city to the smart city healthcare. The wireless sensors play a major role in making these applications work as they are desired. These tiny, light-weight and low battery-powered sensors make the smallest of the smallest device communicate in an IoT environment. All of these applications require hundred to thousands of nodes to solve a purpose. Routing in such energy constrained network becomes a challenging task, so scalability in IoT is one of the major challenges that need to be solved. Routing protocol for low power and lossy networks (RPL) is one of the protocols developed by the Routing Over Low Power And Lossy Networks (ROLL) group to meet the QoS requirements for various IoT based applications. However, the existing versions of RPL fail to provide better results when the number of nodes in the network is increased. Our proposed protocol Clustered Additive RPL (CA-RPL) uses a weight based clustering technique to meet the efficiency of a scalable network. In addition to that, the path selection for data transmission is done by considering three parameters namely Expected transmission count (ETX), hop count and available energy. It is observed that the proposed approach outperforms other approaches in terms of packet delivery ratio, end to end delay and energy consumption in the network.

Keywords: IoT · RPL · Cluster · Additive

1 Introduction

IoT [1] is basically the communication between everyday objects that are connected through the Internet, capable of collecting and analyzing data from the surroundings and then transferring the obtained information to the required destination for further processing. If we talk about the layered architecture of IoT, it consists of four layers starting from the bottom as follows: the sensors layer, network layer, the management service layer and the topmost application layer.

The network layer mainly consists of the routing protocols which are designed for efficient communication between the devices or routers and sending the resulted useful information to the destination for further processing. Several IoT

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applications like healthcare, agriculture sectors, military and non-military applications use a large number of nodes to form a networking environment, which opens the issue of scalability in an IoT network. The routing protocol must be designed in such a way that it performs well in environments where the number of nodes may range from hundreds to thousands. Performing clustering in such an environment can be one of the solutions to achieve network scalability. In the clustering approach, there is cluster formation and from each cluster, a cluster head is selected. The task of the cluster head is to aggregate the data from its cluster members and forward it to the sink for further processing.

Some of the cluster head selection parameters that need to be considered while using clustering on routing protocols for a scalable network are:

- As we know, the sensor nodes in an IoT environment have very limited battery power. So battery power can be one of the parameters considered for selection of cluster head.
- The cluster head holds the responsibility to send data to the base station through other cluster heads. So in order to reduce the number of cluster heads, the degree of connectivity can be considered as another parameter for selecting a cluster head. A higher degree of connectivity means large sized clusters are formed, thereby reducing the number of cluster heads.

By allowing the protocol to operate in a clustered environment, we can reduce the energy consumption, minimize routing overheads, thereby, increasing the lifetime of the network. There are several routing protocols developed for IoT based scenario that work on reliable data transmission from source to destination. RPL [2] is one of the IoT based routing protocols which is designed for low power and lossy networks (LLN). It is a distance vector routing protocol where each router updates other neighbours about the network topology periodically. The routing process in RPL starts by forming a Destination Oriented Directed Acyclic Graph (DODAG) topology containing a single root known as DODAG root. Networks can have more than one DODAG's, each identified by a unique DODAG ID. At each RPL node, a rank is calculated based on some objective function. Using the rank information, the node tries to select the best parent through which it forwards the data packet to the root. RPL uses four control messages to construct the DODAG topology, they are DODAG Information Solicitation (DIS), DODAG Information Object (DIO), DODAG Destination Advertisement Object (DAO) and DAO-ACK. RPL uses trickle algorithm which decides how often the node sends these control messages to update the network.

The rest of the paper is organized as follows: In Sect. 2 all the related works are mentioned. In Sect. 3, the proposed work is described in detail with example diagrams. In Sect. 4, the performance of the proposed approach is compared with the existing approaches. Finally, the paper is concluded in Sect. 5.

2 Related Work

There are several works in the literature where authors have proposed different methods to calculate the rank of a node in RPL, and select parent based on that rank. Mohamed et al. [3] proposed an objective function which chooses a path having a high transition probability. The transition probability is calculated by taking two metrics into account i.e. transmission delay and residual energy. However, it did not consider the ETX metric for detecting lossy links. So, it may result in choosing inefficient routes.

The authors in [4] have combined four routing metrics namely ETX of the link, REC of the link, RANK of a node and minimized delay metric, to select the most optimal path for data transmission. However, energy consumption of the node has not been taken into account for studying the network lifetime of nodes.

Iova et al. [5] have proposed an Expected Lifetime metric which evaluates the residual time of each node i.e. the time before which the first node runs out of energy. It aims to maximize the lifetime of each node. The authors have compared their proposed approach with several other routing metrics and found their method to be better in terms of longevity of the network. However, the performance metrics like packet delivery ratio and end-to-end delay does not offer good performance.

Kamgueu et al. [6] have proposed an energy-based routing metric to be used by the objective function in RPL. Although the protocol performs better in terms of energy. consumption, there is no consideration of link quality metrics for path selection, which may result in choosing lossy and inefficient routes.

Sanmartin et al. [7] have proposed a sigma-ETX metric to solve long hop problem. The standard deviation of ETX value for each path is calculated, and the path having the lowest standard deviation is selected as the best path. However, energy metric is not taken into consideration for selecting the path, which can result in faster energy depletion of some nodes.

However, the concept of clustering is not applied anywhere in the above approaches. The clustering technique can solve the issue of scalability in a large network. In clustering mechanism, only the cluster heads are responsible for forwarding the data packets to the required destination, thus reducing the amount of traffic in the network. As a whole, the energy consumption is reduced which increases the network lifetime. Clustering can be one-hop or multi-hop. In one-hop clustering, the cluster members are at one-hop distance from the cluster head, so the distance between any two clustered members in a cluster is at most two. Whereas in multi-hop clustering the members can be at multi-hop distance from its cluster head.

Chinara et al. [8] have done a simulation survey for one hop clustering algorithms in mobile ad hoc networks and have proved that consideration of multiple parameters for clustering ensures a better result in terms of the number of clusters, network lifetime and the number of members per cluster. Another weight based clustering algorithm (WBCA) has been proposed by the authors in [9] that considers the degree of connectivity and available battery power of a node to calculate the weight of each node to be considered for cluster head. Few other one-hop weight based clustering algorithms have been proposed in [10–12].

The proposed protocol Clustered Additive - RPL (CA-RPL) uses a weight based clustering to select cluster heads. In addition to it, our method calculates rank of a node by combining three metrics additively, the metrics are Expected transmission count (ETX), hop count (HC) and available energy (AE). The result shows that our approach outperforms the traditional approaches in terms of packet delivery ratio, end to end delay and energy consumption. Thus, in a network consisting of large number of nodes, CA-RPL proves to be well fitted for a scalable network.

3 Proposed Work

In our proposed work CA-RPL, we have applied a weight based clustering algorithm to form clusters and select cluster heads. Only the cluster heads trigger the objective function, where the rank of the cluster head is calculated by combining three routing metrics (ETX, HC, AE) additively. Using the rank information, the cluster head selects its parent cluster head through which it forwards the data to the destination.

The proposed protocol CA-RPL works as follows. Initially, the DODAG root broadcast DIO packets to all reachable nodes with information about rank, objective function, ETX and residual energy of the node. Upon reception of DIO packets, the cluster formation process starts. The algorithm for cluster head selection is called. For each node within the transmission range of the receiver, the weights are calculated as given in Eq. 1:

$$W_d = a_1 * D_d + a_2 * E_{residual} \tag{1}$$

Where $\mathrm{D_d}$ is the degree difference of a node d and $\mathrm{E_{residual}}$ is the residual energy of a node d. The degree difference [9] is can be calculated as given in Eq. 2:

$$D_d = \mid C_d - K_d \mid \tag{2}$$

Here $\mathrm{C_d}$ is the degree of node d and $\mathrm{K_d}$ is the mean connectivity degree of node d. The mean connectivity-degree can be calculated as:

$$K_d = \sum_{j=1}^{C_d} \frac{C_{dj} + C_d}{C_d + 1} \tag{3}$$

where $\mathrm{C_d}$, $\mathrm{C_{dj}}$ denotes degree of connectivity of node d and degree of connectivity of $\mathrm{j^{th}}$ neighbour of node d respectively. The residual energy $\mathrm{E_d}$ is calculated from the power trace module present in Contiki OS.

The node having the highest degree difference and highest remaining energy should be considered as the cluster head. Therefore, after the weights of the node are calculated as given in the Eq. 1, the one having the highest weight is selected as the cluster head. In this way, the clusters are formed and cluster head gets selected. When a cluster head receives a DIO packet, it calculates its rank as given in Algorithm 1, and based on this rank information it chooses its next hop parent to forwards the data packet. But, if the non-cluster head node receives the DIO packet, it chooses the cluster-head node in that cluster as its preferred parent.

In the maintenance phase of CA-RPL, if a new node wants to join the DODAG, the node broadcast DIS message in the network. If a non-cluster-head receives the DIS packet, it discards the packet. And if the cluster head receives the DIS packet within its vicinity, the cluster head sends DIO message to the node that wants to join the DODAG. The transmitter of DIS then sends DAO message to choose that cluster head as the preferred parent. If the DIS message received by the cluster head is not its vicinity, the DIS transmitting node calls Algorithm 1 for parent selection.

Algorithm 1. Rank calculation using additive approach by cluster heads

```
Require: Node ID and rank of parents
Ensure: Select the parent through which path cost is minimum
Let $P_1, P_2, ..., P_n$ be the parent list for a node X.
$Preferred\_Node\_Rank$ = INFINITY
for $Parent(P) \in P_1, P_2, P_3, ..., P_n$ do
    $Rank(Child) = Rank(P) + c(i,j)$
    $c(i,j) = \alpha_1 * c_{ETX}(p) + \alpha_2 * c_{HC}(p) + \alpha_3 * c_{AE}(p)$
    if $Preferred\_Node\_Rank > Rank(Child)$ then
        $Preferred\_Node\_Rank = Rank(Child)$
        $Select\_Parent = Preferred\_Parent\_Id$
    end if
end for
RETURN $Select\_Parent$
```

The routing process can be better understood with the help of an example topology as mentioned in Figs. 1 and 2. In Fig. 1, there are seven clusters and each cluster has a cluster head in it which holds the responsibility to transmit the data to the sink. Figure 2 shows the communication between cluster member and cluster head. CA- RPL follows multi-hop inter-cluster communication between cluster head and sink and single hop intra-cluster communication between cluster members and cluster head. Single-hop intracluster communication shows good performance in terms of consumption of energy than multi- hop [13,14]. For achieving a scalable network, multi-hop inter-cluster communication is better than single-hop [15]. In Fig. 1(a), node I chooses path I→J→K→S, L chooses path L→M→N→S and O chooses O→N→S to forward the packet to the sink S. The path selection strategy can be explained from the Fig. 1(b). The path is selected on basis of three parameters i.e. ETX, Hop count and available energy. These three parameters are combined additively to form our required objective function, and based on the objective function the rank of the node is calculated. Node I can choose node J, M or L as its preferred parent to forward the data. To select the best parent among these, the rank of node I is calculated as given in Algorithm 1. For example, in this case, rank of I through J can be calculated as follows:

$$\begin{aligned} Rank(I) = Rank(J) &+ \frac{1}{3} * \frac{ETX_{i\to j} + ETX_{j\to k} + ETX_{k\to s}}{3} \\ &+ \frac{1}{3} * (HC_{i\to j} + HC_{j\to k} + HC_{k\to s}) \\ &+ \frac{1}{3} * \frac{(\frac{1}{AE_i} + \frac{1}{AE_j} + \frac{1}{AE_k} + \frac{1}{AE_s})}{4} \end{aligned} \tag{4}$$

The ETX value for each link is calculated using the following formula:

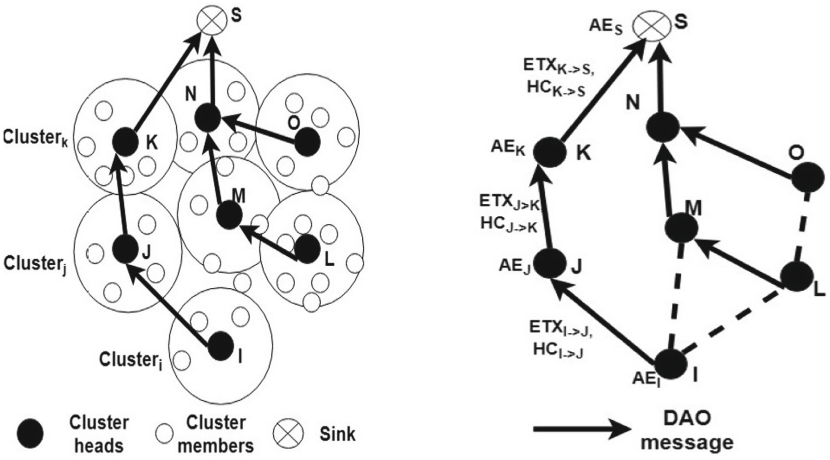
$$ETX_i = \frac{s+f}{s} \tag{5}$$

where s denotes the number of packets successfully delivered to the neighbour node and f denotes the number of packets failed to be delivered. As, we can see from the equation that the ETX value is inversely proportional to the number of packets successfully delivered, therefore, the path having minimum average ETX value is preferred for forwarding the packets. The available energy of each node is obtained from the power trace model available in Contiki OS. The average available energy in a path can be calculated using the following equation:

$$AE(p) = \frac{\sum_{i=1}^{n} \frac{1}{AE_i}}{n(p)} \tag{6}$$

In the equation, AE(p) denotes the available energy for a particular path p which is a ratio of two quantities namely available energy of a node (AE_i) and the total number of hops n(p) in that path. Here, we are taking the reciprocal of the energy metric because the metric needs to transform into a minimizable metric for rank calculation.

Similarly, Rank of I is calculated through parent M and parent L. Node I select node J as its next hop instead of node M and L since it finds that through node J it obtains lower rank, which means that the path cost is minimum if node I transmits the data packet through J. Following the similar method, node L and node O selects M and N as its preferred parent for data transmission. Figure 2 shows the communication between cluster members and cluster head within a cluster. In $cluster_i$, node I have the highest value of weight i.e. 20, so that node is chosen as the cluster head, and other nodes act as cluster members. When any cluster member in $cluster_i$ receives DIO message from cluster head I, it transmits DAO packet to select I as the preferred parent. So, as shown in this figure all the cluster members in $cluster_i$ select the node I as their preferred parent. And if the cluster member has more than one option to choose the cluster head, then it sends DAO packet to the cluster head having the lowest rank. As in this case, the cluster member CM has two options, it can send DAO to cluster head I or J. Here, we assume that node J has lower rank value than node I, so it selects node J as preferred parent.



(a) (b)

Fig. 1. Custer head selecting another cluster head as its parent for data transmission (Inter-cluster communication)

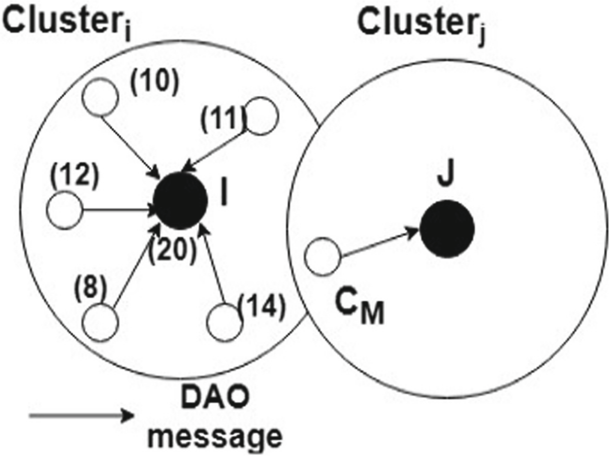


Fig. 2. Cluster members selecting cluster head as the preferred parent for data transmission (Intra-cluster communication)

4 Result and Discussion

The proposed protocol is simulated using cooja simulator in Contiki OS in a 100 * 100 square area with the number of nodes varied from 50 to 600. The simulation parameters are shown in Table 1. Network parameters like packet delivery ratio, average end to end delay and average radio ON time are used to compare the efficiency of CA-RPL in a large network. The result of the proposed work is

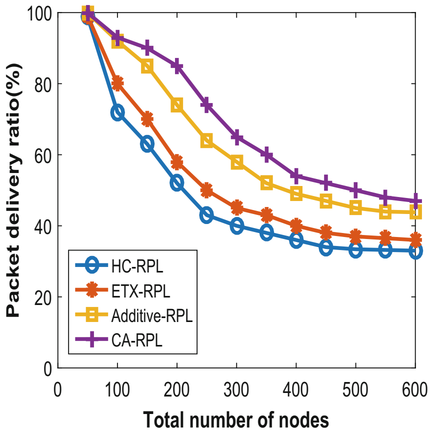


Fig. 3. Packet delivery ratio

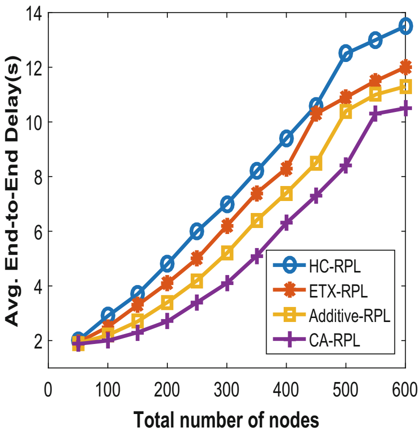


Fig. 4. Avg. end to end delay

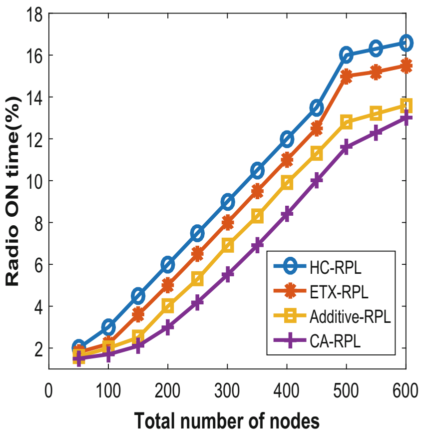


Fig. 5. Avg. radio ON time

compared with the earlier existing versions of RPL i.e. ETX-RPL and HC-RPL that uses objective function MRHOF and OF0 respectively. Our method is also compared with Additive-RPL which calculates the rank as mentioned in proposed work section, but it does not apply clustering technique in it.

Figure 3 shows the packet delivery ratio comparison of four approaches in RPL. The packet delivery ratio can be calculated as the ratio between the total number of packets received by the sink to the total number of packets sent to the sink. We observe that the proposed approach CA-RPL shows higher packet delivery ratio as compared to other approaches. HC-RPL and ETX-RPL use hop count and ETX values respectively to select the best route. In HC-RPL, it chooses path which needs to be traversed with least hop count to reach the sink

Table 1. Simulation parameters

Parameters	Value
Routing metric	ETX, HC, AE
DIO min	12
DIO doublings	8
RDC channel check rate	16 ms
RX ratio	10–100%
TX ratio	100%
TX range	50 m

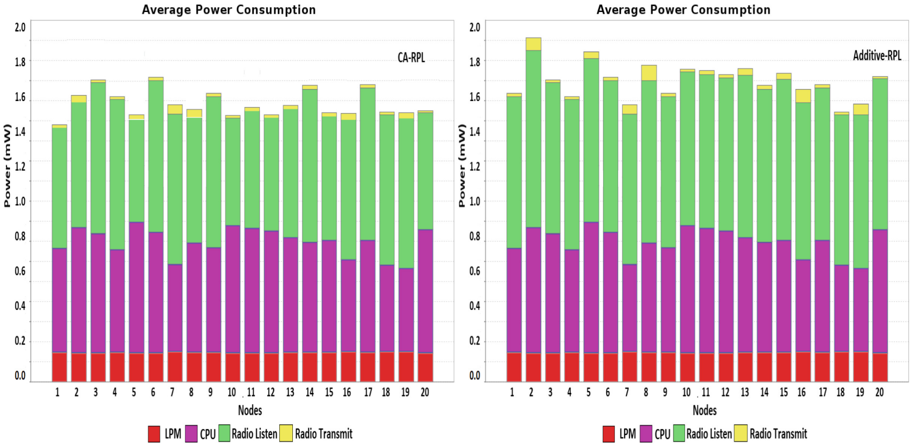
but it does not consider link metric like ETX, therefore it might happen that the path selected would be congested enough to drop the packet, and hence it shows the least packet delivery ratio as compared to remaining three approaches. In ETX-RPL, although it considers ETX value as its path choosing metric still it does not considers node metrics like residual energy. In Additive-RPL, the path is chosen by combining three metrics additively by giving equal weight to ETX, HC and available energy metrics. And finally, in the case of CA-RPL we apply the method of clustering to increase the packet delivery ratio when the number of nodes is large. Since in CA-RPL only the cluster heads of respective clusters are responsible to forward the packet, the number of nodes taking part in communication is reduced significantly, so the probability of a packet to reach the sink increases.

Figure 4 explains the results obtained for the average end to end delay. The end to end delay is calculated by taking the difference between the time a packet was sent from a node and the time when that packet was received by the sink. The average end to end delay is calculated by taking the average of all delay of packets generated by the whole network of nodes. In the figure, the delay of CA-RPL is less as compared to other approaches. Since only the cluster head holds the responsibility to transmit the data to the sink, the number of intermediate nodes required to send the data from the source node to the sink decreases, thereby reducing the delay.

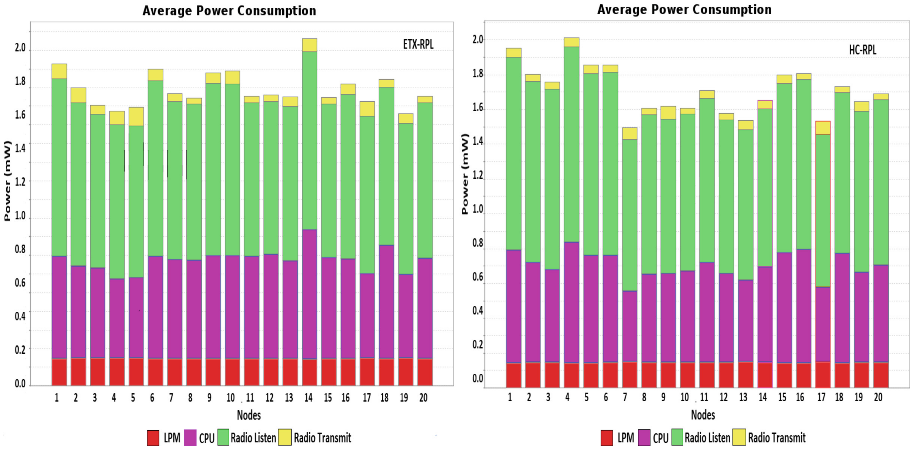
Figure 5 shows the comparison of radio ON time of all the approaches. Radio ON time considers the radio transmit time, radio listen time, CPU time and the time in which the nodes operate on low power mode i.e. LPM time. Here, the average values of radio ON time of each node in the network is considered. If the radio of a node is kept ON for a lesser amount of time, then less energy will be consumed, hence it will increase the network lifetime. In the case of HC-RPL and ETX-RPL, they do not consider the energy node metric for path selection, so their energy consumption is more as compared to other approaches. In CA-RPL, since only the cluster heads are required to transmit the data packets to the destination, so the non-cluster heads keep their radio OFF most of the time.

Therefore, a significant improvement in the radio ON time is observed in the case of CA-RPL.

In Fig. 6, CA-RPL shows significantly less average power consumption than other approaches in terms of radio transmit, radio listen, CPU and LPM time. So, there is an overall increase in network lifetime in case of CA-RPL. Figure 7 shows the average duty cycle of nodes in the network. In this case, the CA-RPL shows a significant decrease in the duty cycle of the nodes as opposed to the other three approaches.

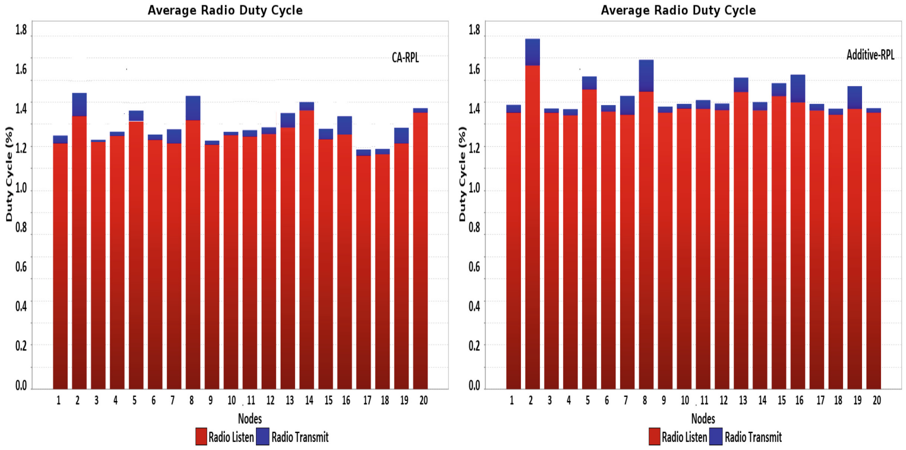


(a) CA-RPL (b) Additive-RPL

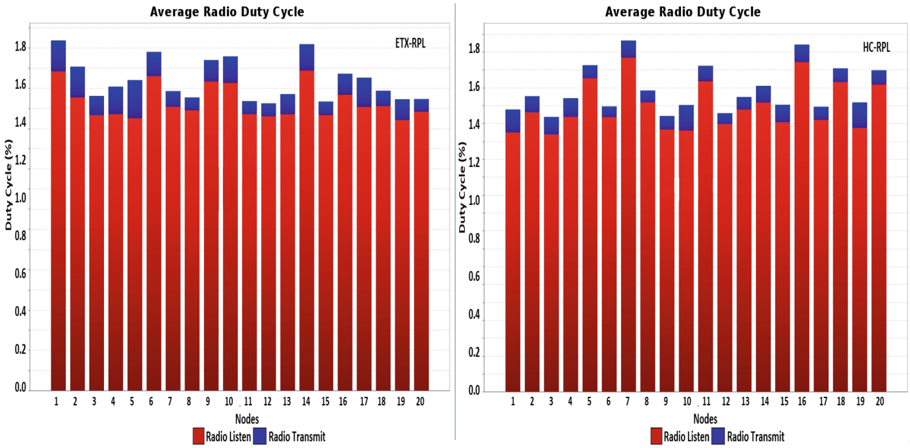


(c) ETX-RPL (d) HC-RPL

Fig. 6. Comparison of average power consumption of first 20 nodes for all approaches



(a) CA-RPL (b) Additive-RPL



(c) ETX-RPL (d) HC-RPL

Fig. 7. Comparison of average duty cycle of first 20 nodes for all approaches

5 Conclusion

When it comes to routing data over a large network with energy constrained nodes, scalability is one of the major issues that the network has to face. In a large network, there is more probability that the packets are being collided, thereby giving poor results in terms of network parameters. So the routing protocols developed for IoT based applications must consider necessary parameters to give better results even when the network size is large. The existing approaches ETX-RPL and HC-RPL consider only a single routing metric for path selection, which cannot satisfy all the QoS requirements of the applications for which it is developed. Also, their performance gets degraded when the number of nodes in the network is increased. Additive-RPL performs better than those two approaches because it considers three parameters instead of one for choosing the best path to route data. CA-RPL applies clustering technique in it, where the cluster heads are selected on basis of battery power of a node and degree connectivity of a node. The simulation results show that our proposed approach CA-RPL outperforms the other three approaches.

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