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Performance Evaluation of Multiple Objective Functions for Parent Selection in Routing Protocol for Low Power Lossy Networks

Ramadevi Chappala[1*], Prof. E. Sreenivasa Reddy[2], J.Bhargav[3], G. Radhika[4]

[1] Assistant Professor, Department of Computer Science and Information Technology, Chalapati Institute of Engineering and Technology, Guntur, Andhra Pradesh, India
[2]Dean & Professor, Department of CSE, Dr.Y.S.R. ANU College of Engineering, Acharya Nagarjuna University, Guntur, Andhra Pradesh, India
[3]Head of the Department , Assistant Professor, Department of CSIT, Chalapathi Institute of Engineering and Technology, Lam, Guntur, AndhraPeadesh
[4]Assistant Professor, Department of CSE, School of Engineering & Technology, SPMVV, Tirupati, Andhra Pradesh, India
*Corresponding Author: Ramadevi Chappala ramadevisibbala2007@gmail.com

Abstract

IoT supports a variety of uses, each one of which has its own unique needs. For instance, the basic monitoring programs may accept delays in some data transfer but, mission-critical systems cannot. The metric or constraint (ETX, Energy, etc.) chosen for the routing method, data amount, and necessary quality of service determine the lifespan and efficiency of IoT sensor networks. The RPL routing protocol for low power and lossy networks uses the objective function (OF) to build a Destination Oriented Directed Acyclic Graph (DODAG) based on a set of metrics and constraints. The OF has as the main function to select and specify the best parent or the optimal path to reach the destination. However, proposing an adequate OF in Low Power and Lossy Networks (LLNs) presents a substantial challenge. Modern methods, however, primarily concentrate on a single measure or restriction, which leads to the protocol performing poorly. A thorough analysis of RPL across critical performance parameters is required to comprehend the protocol behavior for various metrics (single and combined). Researchers have put forward a number of application-specific routing algorithms that do not provide a standard parent selection procedure. In order to improve performance in all ways, a variety of RPL optimizations- have been developed that combine the various routing metrics. This paper gives the comparative analysis of existing Objective Functions that are based on different routing metrics and concludes that various OFs used in our research work. Performance evaluation parameters have been extended to PDR, power consumption, hop count, throughput, overhead, energy exhaustion and packet loss for different network size and link quality. Results are obtained using NS-3 simulator.

Keywords*:* ETX, Internet of Things, LLN , Load Balancing, Objective Functions, RPL.

1. INTRODUCTION

In the present years, billion of sensors had been deployed throughout the globe, wherein our planet comes to be a futuristic network known as Internet-of-Things (IoT) sensor network. Within the IoT ecosystem, gadgets are embedded with constrained energy, memory, and processing elements which are enablers for a huge number of IoT applications. Today, such networks are utilized in diverse applications of our day-to-day life as smart transportation, smart healthcare, smart factory, smart home, and smart agriculture, and so forth [1]. Building automation (RFC 5867), Industrial control (RFC 5673), home automation (RFC 5826), and urban environment (RFC 5548) are the four applications in which the routing requirements are standardized by IETF ROLL in 2014 [2]. RFC 6550 identifies a Routing Protocol for Low-Power and Lossy Networks (RPL) by the IETF ROLL team members in 2012. Now for LLNs the RPL became the standardized routing protocol. However, because of their restricted resources, low power and lossy networks will face network contention whenever the traffic load crosses the available capacity [3]. This congestion hassle induces packet loss ratio and hence, degrades Wi-Fi or any wireless channel throughput. IoT networks are facing many issues and these issues encompass link quality deterioration, network congestion, failure of gadgets that affect their overall network performance. Various Objective Functions may be designed as a way to gain unique optimization standards and fulfill the necessities of a selected application. In order to evaluate the path with least value, RFC 6719 is determined and is used in RPL implementations which internally uses Expected Transmission Count (ETX). While DODAG construction, by using the Minimum Rank with Hysteresis Objective Function (MHROF) along with the ETX metric, nodes tend to pick out parent node along with the greatest link quality and least hop-count towards the base node. Although choosing the base node with better link property is a perfect decision, still it causes a load imbalancing issue in RPL topology. The load imbalance become critical in few cases where the traffic pattern and distribution of nodes are diversified. Nodes that are near to the base node have more number of child nodes with acceptable quality links will get and forward maximum number of packets which may rapidly drain their battery life. To address the specified drawbacks, the author suggest an Objective Function (OF) primarily depending on the bandwidth requirement of individual devices connected in DODAG. Based on node and link metrics , RPL construct Destination Oriented Directed Acyclic Graphs (DODAGs) is a distance vector protocols[4]. Both downstream and upstream traffic is possible in tree like topology DODAG , built according to an Objective Function (OF). OF is used to evaluates the rank primarily based on a few routing metrics which incorporates hop count, delay, energy, and so on. The preferred parent node can serve more than one child in RPL if it selected as a parent node. As a result, the strained preferred parents will become weak nodes as their energy is down to unload much faster than the remaining nodes. After accomplishing a complete assessment, it is finalized that the modern OFs construct a topology and face unbalanced traffic in congested nodes particularly with the primary hop nodes from the base node.

Presently, there may be no specific method to come across or keep away from the congestion in RPL protocol. To eliminate selecting parents with a maximum hop count and bad link quality, RPL protocol utilizes a simple parent selection mechanism [5]. Still, these strategies might additionally bring ping-pong means frequently changing its state from one to another. Consequently, the parent nodes are moving from one to another when this problem occurs on a particular node. In AHCCP, through control messages by the parent nodes the presence of congestion will be informed. In this situation, switching of parent from one to another will be taken by the child node based on the condition. The proposed solution can mitigate congestion by exchanging parent nodes with the least load and eliminate the ping-pong effect. Bottleneck, early node death, energy hole, thundering herd, and poor network performance are happened in network due to load Imbalance. These problems seveourly affect the RPL network when a node is in one hop to sink node. In order to hold these issues we need effective load balancing mechanisms.

But there is a problem associated with Adaptive Hybrid Congestion Control Protocol(AHCCP)**.** Parent selection and route optimization are very difficult to handle in RPL topology, though choosing the parent with the good link quality still causes a load balancing problem. In some cases where nodes dissimination and traffic sample are heterogeneous, the loadbalance becomes difficult. Though the nodes that are close to the base node and that have many children with better-quality links will obtain and move forward a huge amount of packets which may rapidly exhaust battery life and finally it may initiate break the network topology partially along with reliability.

To tackle the above issues, Cache Based Multipath Load Balancing(CBMLB) Algorithm is proposed. Firstly, a novel OF has been introduced using a new techniqe, to get a better load scattering among the candidate parents, in an attempt to balance the load traffic and keep the battery lifetime thriving for a longer time. Particularly, the parent having less number of children will be choosen as a selected parent node. Finally, the balance has been getting by minimizing total of selected parent with respect to the least rank, and confidently has minimum number of children.

To overcome the problem associated with CBMLB we suggest modified bandwidth Adaptive Congestion Window(ACW) , a novel load-balanced objective function for 6LoWPAN to achieve an efficient load scattering among nodes in LLNs and battery lifetime thriving for a longer time to come, which in turn to obtain good reliability of the network. A new mechanism has been utilized to count the total of child nodes for each parent without initiating any additional overhead and then push into the DIO. So, stonger fairness of child node distribution has been obtianed along the RPL DODAG construction process. Although methods proposed in the literature provide partial load balance and they fail to provide load balance of resources such as buffer allocation and bandwidth. And it attempts to provide RPL load balancing based on bandwidth distribution among candidate parent nodes.

The paper is divided into a number of parts. The remaining paper is organized as follows. Section II describes the background details of the RPL. Section III explain about the RPL OFs used in 6LoWPAN to overcome the problems associated with the loadbalancing. Finally, AHCCP, CBMLB and ACW will be compared against the OFs used within section IV. In section V we conclude the work.

2. BACKGROUND AND MOTIVATION OF RPL

The Routing Over Low power and Lossy Networks (ROLL) working group of the Internet Engineering Task Force (IETF) has suggested RPL as the IPv6 Routing Protocol for Low power and Lossy Networks (LLNs) [6]. The fundamental concept of RPL is to partition a network architecture into several Destination Oriented DAGs (DODAGs), one for each sink node, and a Directed Acyclic Graph (DAG) on top of that. The DAG prevents cycles in the routing path and follows it in the direction of the sink node. It is referred to as DODAG when a collection of sending nodes forwards packets in the direction of the destination node. RPL, an IPv6-based IETF protocol standard for LLNs, has the ability to meet IoT needs since it provides a variety of advantages. Below [7] is a list of RPL's positive attributes:
1) The ability to support multipoint-to-point (MP2P), point-to-multipoint (P2MP), and point-to- point (P2P) traffic flows from node-to-node.
2) During routing, dynamic route selection and auto-configuration.
3) Implementing both global and local repair techniques, loop detection/avoidance during packet forwarding, and initiating repair (if loop arises)
4) Separate packet forwarding and routing optimization processes (reducing latency, energy, etc.).
5) Use of a range of connection layers, including limited or possibly lossy ones like PLC (Power Line Communication) or low-power wireless.

A. IoT Layered Architecture

The fundamental layered architecture of the IoT with an RPL network topology is shown in Figure 1. The service management layer, the application layer, and the business layer are the top three levels of the Internet of Things architecture and they provide comprehensive analysis and administration of the services offered by IoT [8]. The perception layer is made up of intelligent sensors that acquire details from their surroundings or from the object to which they are connected, and actuators that respond favorably to changing conditions. At the perception layer, the supporting protocols may be wired (such as Ethernet, PLC, etc.) or wireless (such as ZigBee, Wi-Fi, etc.). RPL, the default routing protocol for Internet of Things applications, is crucial for data routing at the network layer.

Additionally, an RPL Instance with two DODAGs is also shown in this Figure. At the root or border router that connects to the internet, the DODAGs are terminated. The sensor nodes that gather data from the environment are known as hosts or end devices. Through intermediary nodes, this information is sent to the sink or border router. Constraint-based routing, which allows constraints to be imposed on both connections and communication nodes, is what distinguishes RPL. The constraint (Energy, Latency, Hop count, ETX, etc.) on the basis of which the route cost assessment is carried out is defined by the RPL OF (OF0/MRHOF). The hosts or end device nodes choose the forwarder nodes (routers) in an effort to reduce the cost of the data transmission channel to the sink. In a DODAG, parents are chosen depending on the limitations or metrics presented by the node next to them. The following three kinds of traffic patterns enabled by RPL are shown in Figure 1:

1) Point to Point (P2P): Two nodes communicating with each other.
2) Point to Multipoint (P2MP): This method involves DODAG root sending DIO signals downstream to network nodes.
3) Multipoint to Point (MP2P): Upward transmission of DAO (Destination Advertisement Object) signals via the DODAG from child to parent or root.

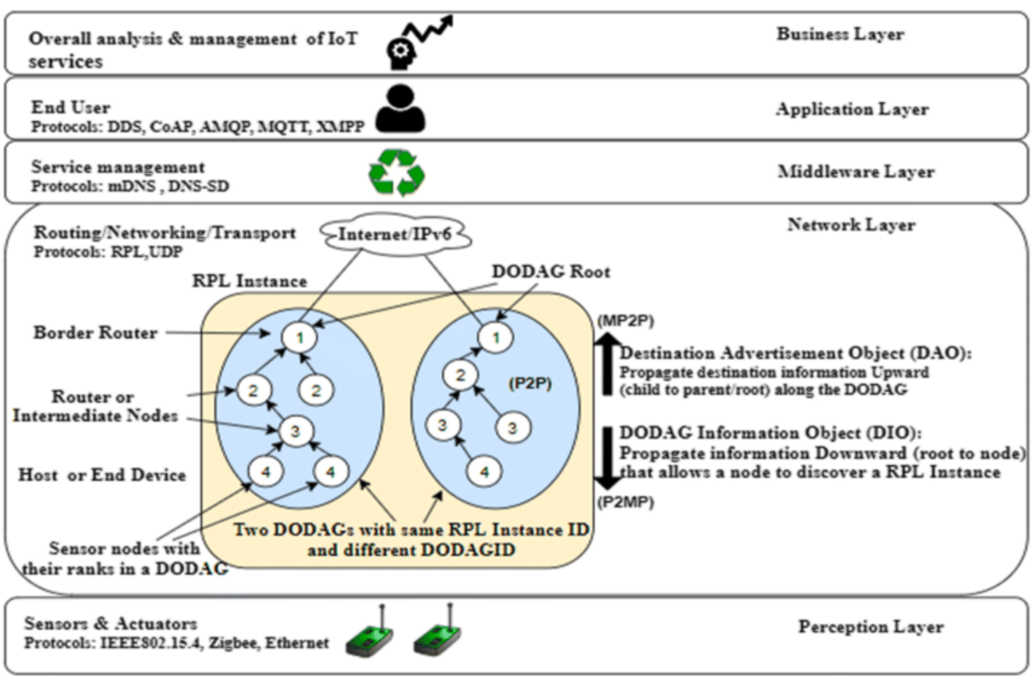

Figure 1: IoT layered structural design with RPL network topology

B. DODAG Control Messages

By using DIO messages, which are published by the DODAG root, network nodes may identify RPL Instances (i.e., a group of related DODAGs) and their configuration settings [9]. For the purpose of choosing and maintaining the network topology, four parameters known as RPL IDs are needed :

1) RPLInstanceID: This identifies a collection of DODAGs that have been optimized based on an OF. A group of DODAGs known as an RPL Instance are identifiable by an RPLInstanceID.
2) DODAG_ID**:** A DODAG inside an RPL Instance may be uniquely identified by its DODAGID in conjunction with the RPLInstanceID.
3) DODAGVersionNumber: A DODAG Version may be uniquely identified by its DODAGVersionNumber, RPLInstanceID, and DODAGID.
4**)** Rank: This indicates where each node stands in relation to the DODAG root.

RPL was created to optimise energy use and provide reliable data reception. RPL provides a collection of ICMPv6 control messages for exchanging DODAG data, including:
(i) DODAG Information Solicitation (DIS)
(ii) DODAG Information Object (DIO)
(iii) DODAG Destination Advertisement Object (DAO)
While the DAO messages provide a downward path from the sink to the senders, the DIO messages are transmitted from senders to the sink node. Any node in RPL has the ability to send a DIS message to request a DIO message from nearby nodes.

There is a lot of research being done to create the optimised RPL versions using the various OFs. A key factor in determining the DODAG topology is an OF. The best parent is chosen from the list of parents based on the least rank value, which is determined by OF utilising several routing parameters. Each node chooses a preferred parent, and then the best path is attempted to be found in terms of many performance parameters, such as less energy consumed, the best link quality, a longer network lifetime, lower latency, and so forth. RPL employs two different measurements.

(1) ***Node metrics:*** The metrics (such as Hop count and Node energy) that reflect the nodes' state.
(*2)* ***Link Metrics:*** The measurements (such as Link Latency and ETX) that show how well-built the links are.

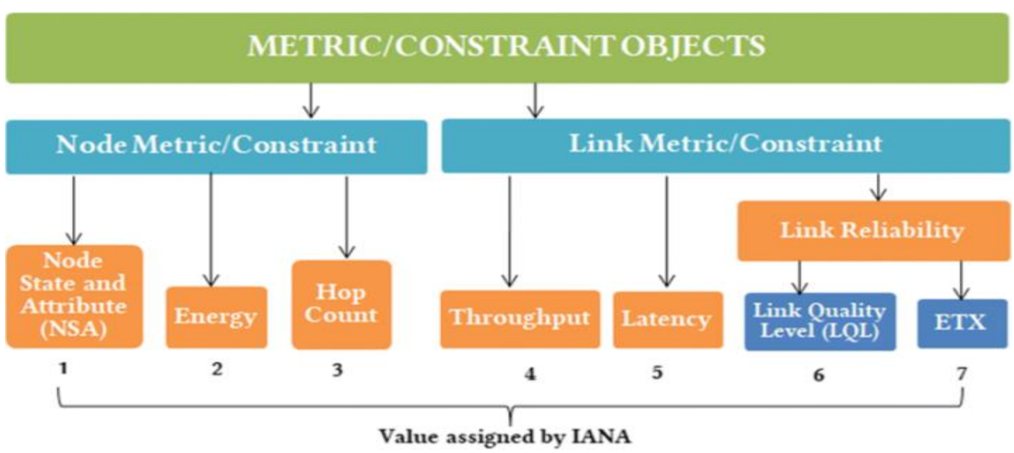

Figure 2: RPL Objective Functions

3. ANALYSIS ON EXISTING RPL OBJECTIVE FUNCTIONS

During DODAG construction, the nodes choose the parent nodes by selecting the least expensive routing path in order to pass their packets in the direction of the sink. Any routing path's cost may be affected by the amount of energy used or the amount of delay encountered. An optimization challenge that relies on an Objective Function (OF) established in RPL is choosing the least expensive routing path. Here, OF specifies the limitations and metrics that will be used while choosing the path to the sink node. The user finds challenging to pick a routing protocol for their particular application due to the lack of standardization and options for routing metrics. There are basically two Standard OFs used in RPL to determine the Rank of a node in DODAG.

A. Standard Objective Functions (OFs)

1) ***Objective Function Zero (OF0):*** The IETF published its first standard, OF0, in RFC 6552 [7] in March 2012. The default routing measure is hop count. This aims to build DODAG in a way where the nodes discover the root node at the shortest possible distance in regard to the total amount of hops (intermediate nodes). The ranking of the nodes is determined throughout the construction mechanism, and each node chooses its parents based on the metric's minimal value. The disadvantage of OF0 is that while RPL is primarily intended to operate in low-power, lossy situations, neither the nodes' battery levels nor the calibre of the links are taken into account by OF0 [10]. Only routes with the fewest hops are selected, therefore these routes may even have links that are unstable and cause numerous retransmissions, which results in larger packet losses. Second, because nodes on shorter paths are frequently used, their batteries are quickly depleted, adversely limiting the network's longevity.

2) ***Minimum Rank Hysteresis Objective Function (MRHOF):*** Another OF that has been standardized by the IETF is MRHOF [11] in RFC 6719. Like previous OFs, it aims to choose the route with an optimized value of a routing measure, but it has the benefit of greater network stability because to the use of a novel notion called "hysteresis". The node modifies its parent node only if the variation between the new and prior metric values is greater than a predetermined threshold value. This applies to any modifications to the DODAG. It may use a number of measures, but two are often discussed in the literature:

a) Minimum Rank Hysteresis Objective Function with ETX (ETXOF): MRHOF uses Expected Transmission Count (ETX) [12] as the default routing metric for MRHOF. It gives the measure of an average number of transmissions required for the successful transmission of the packet. It is given by (1), as

ETX= $1 / (D_f * D_r)$ ------------ (1)

In (1), D_f is the forward delivery ratio defined as the probability for the successful arrival of the packet from source to destination and D is the reverse delivery ratio defined as the probability for the successful arrival of the acknowledgment from destination to source. Higher will be the value of $Df * Dr$, more is the probability of a successful transmission of a packet, lesser is the ETX value. Lesser ETX value indicates the good quality of a link in terms of reliability. The ETX of the entire path is calculated by adding the ETX values of the connecting links along the path and the best reliable path is chosen for the data delivery. According to the simulations performed in [12], ETXOF outperforms OF0 in terms of power, PDR, control overhead, and ETX. Since ETXOF really concentrates on the lossy characteristics of such networks, it is a better solution than OF0 for LLNs. The disadvantage of ETXOF is that it ignores the energy levels of the nodes along its route and solely concentrates on network dependability. The energy of the nodes depletes quicker than that of the others, reducing the network's total lifespan, if the route with the fewest transmissions is repeatedly chosen by data traffic.

b) Minimum Rank Hysteresis Objective Function with Energy: Energy may replace ETX as the best parent selection measure. It selects the route from source to destination that passes via energy-efficient nodes. Each node along the route's energy use is added up, and the path with the lowest total is selected for the data flow. In contrast, it is shown in [11] that MRHOF with energy works well in terms of average power usage, but at the expense of more packet losses and delays. This is due to the fact that it disregards measurements for connection quality and hop count in order to reach the destination, which forces it to deal with link failures that cause higher packet losses and delays.

B. OFs used in various protocols

1) ***Adaptive Hybrid Congestion Control Protocol (AHCCP):*** ETXOF calculates the total sum of ETX values along the route, and often, the path with fewer hops results in a lower summation. However, as more nodes are added, the issue arises. According to observations, a route with fewer hops and a lower ETX summation value has a lower transmission rate. This happens because the network may be restricted by lengthy single hops with high ETX values. Contrarily, a route with more nodes may have an ETX summed value that is larger than the situation stated above yet still have a very high transmission rate. Therefore, if data traffic started using that way, the number of retransmissions would be greatly reduced, and total delays and energy consumption would also go down. The OF has found a solution to this issue by creating a statistic called $ETX_{each\text{-}hop}$ that incorporates both ETX and Hopcount.
In (3) where ETXi is the value of the ETX for the ith link along the route including n nodes, it calculates the overall total of the ETX along the path from a specific node to the root and distributes it among the n number of hops along that path. As a result, a route with a lower $ETX_{each\text{-}hop}$ value is selected for the data traffic flow.

$$Rank(i) = RI+LQ_p+Rank_p \quad \text{---------------} \ (2)$$

$$ETX_{each\text{-}hop} = \sum_{i=1}^{n} ETXi \,/n \quad \text{-------------} \ (3)$$

2) Cache Based Multipath Load Balancing (CBMLB): A new load balancing problem has been found in [13]. The routing characteristics, such as ETX, Hop count, Energy, and others, are now being used by the OFs to choose their preferred parents. In light of current research, it has been shown that these OFs result in the development of a DODAG in which the nodes, particularly those that are extremely close to the sink node, experience the issue of Unbalanced Load distribution. The nodes are servicing several children, therefore some of them get overloaded as a result of the numerous child nodes in their queues. Because of this, they lose energy far more quickly than the others do. These nodes become as bottleneck nodes, and as a result, their lifespan shorten. If the bottleneck node is a sink node, the whole network may be disrupted, adding to the cost of having to repair the entire DODAG. To overcome the aforementioned problems, the authors have suggested a brand-new Load Balancing based Objective Function called Cache Based Multipath Load Balancing (CBMLB). The preferred parent selection is routed using Childset as the routing measure. A node chooses from its parent list the parent it prefers, the one with the fewest child nodes, or the least traffic burden. Three stages can help you understand the changes introduced in the new OF:
a) *Modifying the DIO:* The DIO packet format has been updated to include a new field called Parent_Id in addition to the Instance_Id, Version_Number, and Rank.
b) *Modifying the Utilisation Scheme for New DIO:* Normally, when the sender delivers the DIO message to its children for the first time, they choose it as their preferred parent and broadcast the DIO packets to their neighbours, including their preferred parents as well, who eventually discard them. The DIOs from the kid nodes should instead be used by the parents to determine the value of the Childset, which is an update to the previous statement. The value of Childset is updated, and its rank is determined based on how

many children it is servicing if the new Parent_Id in an altered DIO matches the Node_Id of the receiving parent.

c) *Parent Selection via Load Balancing:* The node will choose the parent from its parent list that is having the lowest rank, i.e., the node with the fewest Childset is picked as the new preferred parent, balancing their load and energy with the others. so, the OF lessens the amount of traffic that the bottleneck nodes must handle, prevents their batteries from depleting quickly, and so increases the network's overall lifespan.

Computation of Rank: The rank of the desired parent PN (with maximum ELT) is then added to the rank_Increase during the transition from node N to PN in order to determine the node N's rank. Node N then informs its neighbours with the revised information on the new bottleneck. Simulations demonstrate that PDR and delay performance figures for Child Count are closer to those of the ETXOF. Even in the worst scenario for delays, it performs best. It also succeeds in detecting the bottleneck nodes and achieving its goals of balancing the total children node distribution and extended lifespan.

c) Modified Bandwidth based OF for an Adaptive Congestion Window: Due to issues like a bottleneck, hot spot, and thunder herd, optimization and performance are in jeopardy. RPL Load imbalance is the end outcome of all these issues. A load imbalance in RPL might decrease the battery life of important nodes in the network architecture and shorten the lifespan of the whole network. Due to bandwidth limitations in the preceding techniques, even if the nodes with leaves are distributed evenly among favored parents, the RPL would still have load-balancing issues. In order to stabilize the network, hop count and ETX are utilized together.

4. RESULTS AND DISCUSSION

The previsous proposed work is carried out with NS-3 simulator. The parameters used in simulation are specified in Table 1. The simulated outcome are noted for different performance metrics such as rate of transmission time, ratio of packet delivery, Overhead associated with traffic, and DODAG Reconstruction time. The performance of the suggested method is tested and the results are compared against AHCCP, CBMLB. Sensing nodes, relay nodes, and sink nodes are the three different types of nodes in a simulation environment. Every node in the network is capable of forwarding, receiving, and sending the packets along with the bandwidth requirement and propagation delay of links among nodes. The proposed algorithm, mBWACW proved to be performing better when compared with AHCCP and CBMLB in terms of Rate of transmission, the overhead associated with the protocols, packet delivery ratio, and DODAG Reconstruction time percentage.

Table 1: Simulation Parameters

Network Parameters	Value
Nodes	30
Area	300mx150 m
Metrics	ETX, Child count, Bandwidth
Transfer range	100 m
Packet transfer rate	25 KB
Simulation Time	150s
Load size	512 Bytes

The productivity of the suggested algorithm is contrasted with AHCCP and CBMLB, in concerning of delay with multiple rates of transmission is shown in Figure 4. And it is noticed that mBWACW is well performed than AHCCP and CBMLB. The delay happens because of the low propagation delay at nodes in the path. The performance of the proposed work in terms of delay in comparison with AHCCP is 52.4% and CBMLB is 27.6% is decreased

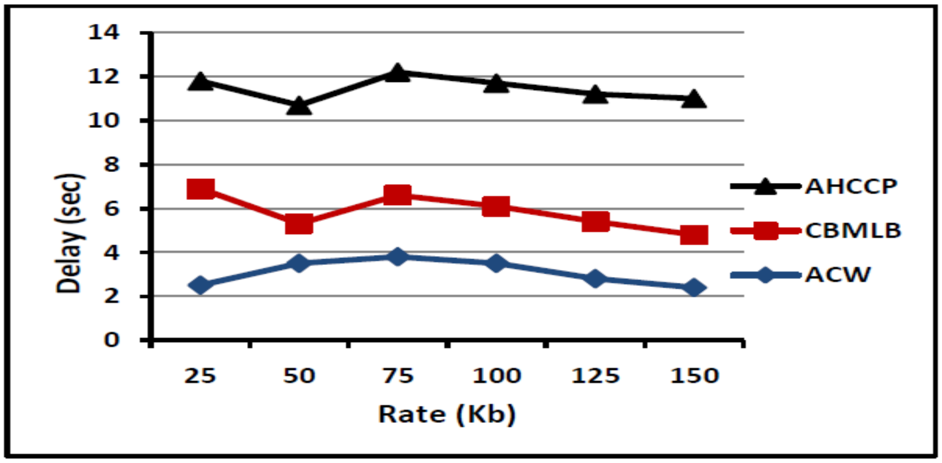

Figure 4: Delay over Rate of Transmission

The execution of the suggested algorithm, mBWACW concerning ratio of packet delivery in correlative with AHCCP and CBMLB is presented in Figure 5 and proved to be performing better. The results are shown at a varying rate of transmission. It can be observed that the packet delivery ratio increases as the rate increases. The ratio of the packet delivery is superior when contrast to AHCCP and CBMLB as the size of the congestion window is depending on the available bandwidth of the path, transmission rate of the sender and the destination node's receiving rate. Packets are dropped when the size of the congestion window is equal to or less than the amount of bandwidth obtainable and also due to unexpected issues in the network for instance node breakdown or link breakage.

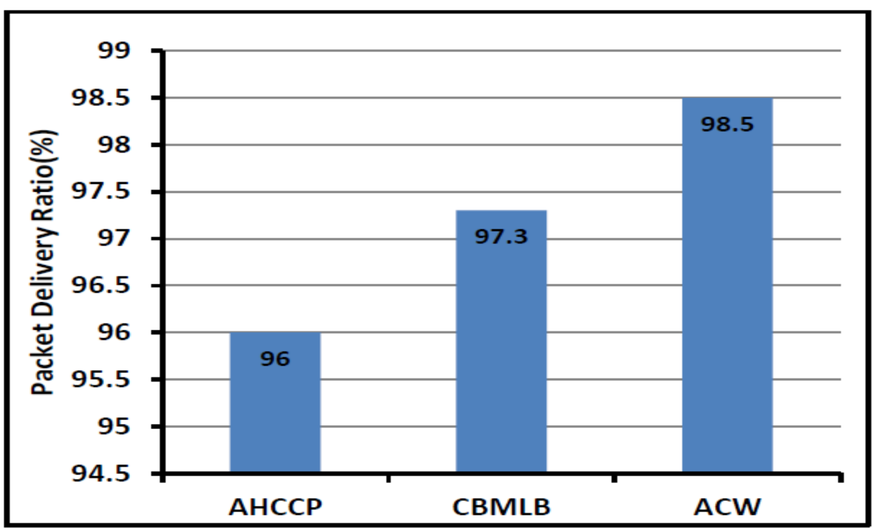

Figure 5: Comparison of Packet Delivery Ratio

To analyze the network load and the traffic pattern, Overhead associated with the Traffic Control is the foremost parameter. Internet Control Message Protocol (ICMPv6) is used to build and keep the RPL network. ICMPv6 and RPL handle control messages and Routing decisions respectively. Control traffic overhead takes place because of the load balancing problems. The simulated results related are shown in Figure 6. We note in such a way that DIO messages had a best part of the traffic control along with DIS, DAO and other control traffic. Due to load balancing and equal distribution of bandwidth, the proposed work shows enhanced and constant performance during network setup. The stediness and load balance of the RPL network is directly proportional to control traffic overhead.

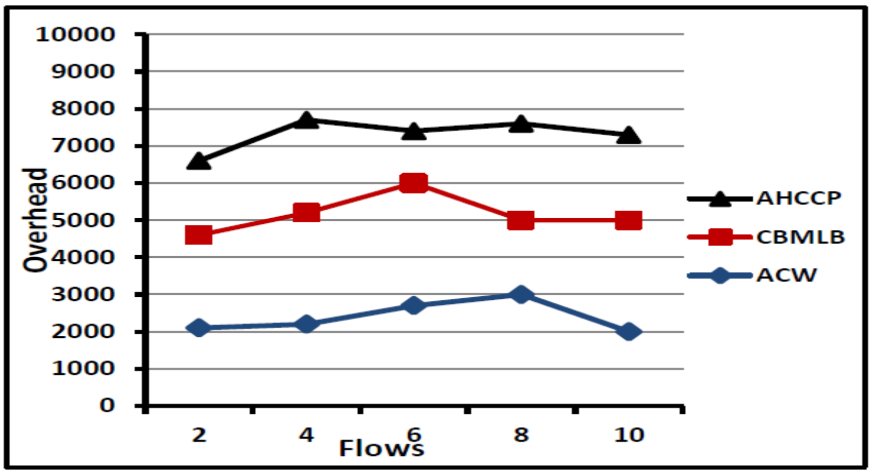

Figure 6: Overhead for varying Flows

Frequent parent switching in AHCCP causes instability in RPL based networks. Network instability causes poor network performance, high control traffic, and energy depletion. Parent switching causes DODAG reconstruction. Figure 7, shows the stability of network outcome in respect of DODAG redesigning. The AHCCP shows high (76%) parent interchange and DODAG redesign in constrast to another protocols. Our suggested technique mBWACW has advanced DODAG redesign (38%) and the CBMLB by 54%. Also, the network come to stable in a less time interval. Hence, mBWACW minimizes the number of parent switches to improve network stability.

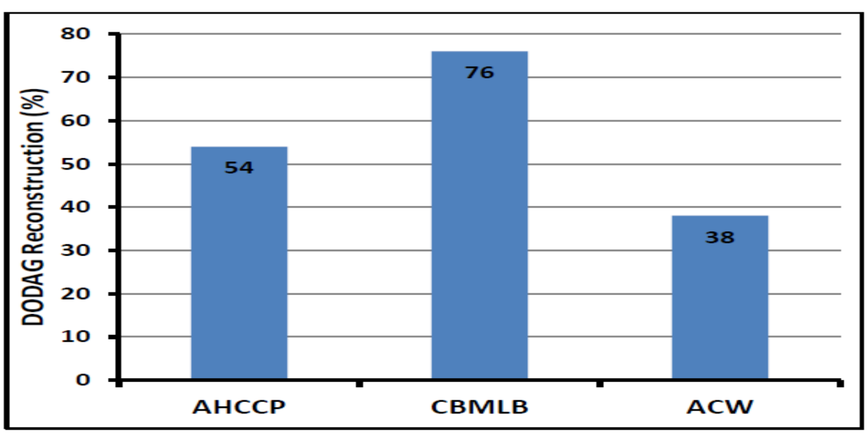

Figure 7: Percentage of DODAG Reconstruction

5. CONCLUSION

The most crucial component of IoT applications is LLNs. These networks can operate in lossy, dynamic contexts with few resources because of an efficient routing. As it offers the optimized implementations of Objective Functions for the optimum parent selection, RPL emerges as the ideal choice for LLNs. The authors have suggested numerous objective functions that use various routing metrics alone or in combination, thereby meeting the needs of applications that seek high dependability, low PDR, minimal overhead, and quick DODAG construction. The authors may address any unresolved routing concerns in the future, and by combining multiple routing metrics, more optimized versions of RPL can be created to expand the IoT application possibilities.

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