International Journal on Future Revolution in Computer Science & Communication Engineering
Volume: 4 Issue: 3

ISSN: 2454-4248
531 – 535

Use of Clustering-based Routing Protocols in Low Power and Lossy Networks – A Survey

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Abstract— Internet of Things (IoT) is the one of the emerging field today, which consists of various resource-constrained devices that are limited in resources and work in the lossy wireless network. Therefore, IoT requires efficient routing protocol so that devices can communicate fast and power efficiently. Among different protocols available for wireless networks, Routing Protocol for Low Power and Lossy Networks (RPL) is a protocol specially standardized by IETF for efficient communication between IoT devices. Routing technique is one of the important factors of a routing protocol, which affects the performance of a protocol. In recent years, researchers contributed to improving RPL performance by providing various solutions and clustering is one of those ways to improve RPL performance by using Cluster- parent based Destination Oriented Directed Acyclic Graph (DODAG). In this paper, we discuss the various clustering-based routing protocols in a Low power and lossy networks (LLNs) and concludes that this survey might be helpful for future researchers.

Keywords*- RPL, DODAG, LLNs, Clustering Algorithm, Cluster Parent Set, PDR.*

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I. Introduction

Routing Protocol for Low Power and Lossy Networks (RPL) is a routing protocol specified by IETF for Low Power and Lossy Networks (LLNs)[1][2]. In the Internet of Things (IoT)[3], devices are low power and resource constrained. To communicate devices in fast and power efficient manner, we require protocols that fulfill IoT device's requirement. RPL is a distance vector protocol and uses source routing and is designed specially according to requirements of LLNs[2][4]. RPL provides an efficient way of communication between these devices so that device's resources (bandwidth, power, computation, memory etc.) remain available for long run-time.

After RPL introduction to wireless networks, researchers started to work on improvement of RPL and worked on its improvements. There are various ways to improve RPL like improvement, modification, and the addition of new components to existing RPL standard's routing techniques, objective function, and trickle algorithm. Until now work done on various areas in RPL but we want to focus on routing techniques, as routing technique is one of the key factors in improving the performance of RPL.

In following sections discusses the remaining paper. In the second section gives an overview of RPL, in the third section compares various clustering based routing algorithms and in fourth section conclusion is given.

II. RPL Overview

RPL uses the concept of DODAG (Destination Oriented DAG) based on DAG (Directed Acyclic Graphs) topology[5]. DAG specifies a tree-like structure in which nodes can act as a child and parent nodes for specifying the routes and communication between Low power and lossy networks (LLNs)[1]. DAG also supports bidirectional traffic. RPL also supports one or more DODAGs, which forms an instance and identified by unique ID called RPL instance ID. DODAG construction in RPL done by considering costs of node's link attributes and objective function[4].

Routing in LLNs divided into three categories namely Reactive, Proactive and Geographic routing[1]. RPL is a proactive routing protocol and it supports three types of traffic.

- MP2P: Multi-point to point traffic – for communication between one router to another.
- P2P: Point to Point – for communication between root nodes to any number of routers.
- P2MP: point to multi-point – for communication between any numbers of routers to root node.

A. DODAG construction

In RPL, DODAG constructed in a way that it supports MP2P traffic and optimized for MP2P. A node in RPL has two statuses[1] i.e. grounded and floating. Nodes that have joined DODAG called Grounded nodes and the nodes are nodes that have not joined a DODAG called Floating nodes.

B. Control Messages

It supports three types of control traffic DIS, DAO, DIO[4].

- DODAG Information Object (DIO): DIO message used for construction and maintenance of network topology. The DIO message issued by the DODAG root, which helps to construct a new DAG and then this message sent in a multicast way through the DODAG structure periodically. It contains information regarding DODAG ID, Objective Function, node's rank and metrics for path calculation. After receiving DIO message, the neighboring node sets its own rank based on the rank of a neighbor node and further sends the DIO message to its neighbors[2][4].
- DODAG Information Solicitation (DIS): Floating nodes uses DIS messages for joining the DODAG in case they did not receive DIO messages from the parent node. After receiving DIS message, parent node replies the requesting node with DIO message[2][4].
- Destination Advertisement Object (DAO): It used to back-propagate the information regarding the routing from leaf nodes to the roots. The child node sends a

ISSN: 2454-4248
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DAO packet to its parent node, which again propagated to receiving node's parent node until it reaches the root node. This information thus used to support P2P and P2MP traffics[2][4].

C. Issues In RPL

In RPL[1], firstly a single parent node chosen by each child node in the network and thus forms a topology that uses DODAG structure where communication is provided using parent node, which forwards child node's data further to their parent node until it reaches root node. Root node further forwards data to the destination node using a top-down approach. RPL considers bidirectional traffic and concept of single parent for packet forwarding. However, RPL suffers from the possibility of loops, implicit assumption on bi-directionality of links and use of low-quality links. RPL is limited in the way; if Parent node gets compromise then its child-nodes will remain unavailable until new parent node selected. In addition, standard RPL also limited in a way if the parent is not optimal than its children nodes will suffer as they may benefit from other possible optimal parent nodes. Most of the packet losses are due to inefficient decisions related to routing so unnecessary use of inefficient links leads to poor performance. These inefficient decisions are due to incomplete knowledge of link qualities, inability to utilize that knowledge.

III. OVERVIEW OF VARIOUS CLUSTERING BASED ROUTING ALGORITHMS

In cluster-based routing techniques[1], a cluster of candidate parent nodes gets formed. These set of nodes utilized in multipath solutions and in situations where parent node compromise than optimal node among the candidate parent node selected for packet transfer. Thus, it solves the problem of single-parent failure. Recent studies investigated and used clustering algorithms for routing improvement in RPL in various scenarios. Routing techniques that can use to improve RPL performance [1] are opportunistic routing[6] and network coding[7]. Opportunistic routing uses the concept of multiple paths as these multiple-paths will perform better than the single path networks by using multiple-paths efficiently and combining poor paths together in one or more reliable links, but multiple-paths suffers from coordination problem and duplication of packets, so one has to deal with those issues also. There are protocols which use the concept of opportunistic routing i.e. ORPL[8] (opportunistic routing), CRPL[9] (cluster parent based RPL) etc. While on other hand, coding techniques used in network coding for improving RPL performance[7].

There are various clustering based routing algorithms where researchers worked on problems of RPL and provided their solutions. Here we discuss some of routing protocols, which uses clustering algorithms to provide better results than RPL. These protocols compared at the end of the section in Table I (Comparison between Clustering based routing algorithms).

A. IRPL: Improved RPL

IRPL[10] uses the concept of clustering in network and topology control model. Topology control model, which divides the network into heterogeneous clusters varying in sizes based on their residual energy and according to their relative position inside the cluster. Subsequent nodes are chosen with optimal angle consideration for efficient packet forwarding in inter-ring cluster's communication, which helps in reduction in energy consumption.

Heterogeneous cluster and a cluster-head rotation mechanism used for balancing energy consumption. To balance energy among nodes throughout ring levels; numbers of the clusters are increased in the inner-ring network and thus reducing the number of nodes in the cluster, which helps to attain energy balance between outer ring layer and inner ring layer's energy consumption respectively. Overall energy consumption of IRPL is smaller when compared to RPL[10].

B. ORPL: Opportunistic RPL

Extension of RPL – ORPL (Opportunistic RPL)[8], which improves Packet Delivery Ratio (PDR), achieves a lesser number of retransmissions and low protocol overhead in comparison to RPL. ORPL uses the property of broadcast nature of wireless networks and decides whether to do forward selection or not based on the result after receiving data from other nodes. On receiving a packet, the node decides whether to take part in packet forwarding or not. ORPL fixes RPL issues via considering candidate parent sets (CPS), also considers only those candidate nodes, which are close neighbors of preferred parents. It uses RSSI value and rank value for hop distance and for selecting CPS nodes. In addition, ORPL reduces unnecessary retransmissions by using adaptive MAC retransmit limit.

However, the problem is that preferred parents are decided based on the concept of single forwarding scheme but it is not optimal for multi-path routing. Also as only highest priority successful parent sends ACK in ORPL, which helps in cooperation among parent nodes and gives low protocol overhead but introduces cooperation errors among parent nodes. However, the best part is ORPL achieves 25% to 30% better PDR than RPL and achieves 10% to 40% lower number of MAC layer retransmissions[8].

C. ORPLx: extension of ORPL

ORPL achieves 50% reduction in MAC layer transmissions but it suffers from a large number of duplicate packets due to ACK failures in ORPL as in ORPL only a highest priority successful node sends ACK after forwarding the packet. Therefore, ORPLx[8] uses new MAC layer extension for improving RPL. In ORPLx's MAC-layer retransmit limit depends upon the factors like a number of nodes in parent set, link success rate and link-quality from source to parent-node.

ORPL provides 50% reduction in MAC layer retransmissions, while ORPLx provides 50% reduction compared to ORPL. Therefore, ORPLx achieves 4-5 times reduction in MAC layer retransmission compared to RPL but its PDR decreases to 98-99% compared to ORPL due to its dependence on the accuracy of the forward link quality estimation[8].

D. CRPL: Cluster-parent based RPL

CRPL – Cluster based RPL[9], achieves low end-to-end cost for nodes, 40% higher PDR than RPL, and 20% more PDR than ORPL. Also improves network reliability and provides low delivery cost.

CPRL shares load by multipath so leads to more energy efficient protocol. CRPL handle the issue of preferred parent via using a top-down approach. Top priority is given to preferred parents (nodes with lower cost to the roots) for packet forwarding, also selecting good inter-link quality parent nodes only. CRPL also suffers by using the local forwarding table, which requires additional memory. In addition, a spatial feature not exploited due to use of priority-based selection[9].

E. Efficient topology construction for RPL over IEEE 802.15.4

This protocol uses the concept of cluster tree as in IEEE 802.15.4 and modifies the cluster tree into the cluster- DAG (cluster – directed acyclic graph). IEEE802.15.4 initially designed and used for single-hop networks. Greedy-algorithm used in integration with IEEE 802.15.4 MAC and MAC mechanisms, which optimized to support multi-hop topologies. The greedy algorithm allows scheduling beacons and active parts of super-frame appropriately while minimizing the bandwidth waste and localized scheduling scheme to allocate collision free slots for beacons and data frames[11].

In multi-hop beacon-enabled wireless networks, IEEE 802.15.4 uses super-frame structure to save energy. The super-frame structure allows a node to stay awake during transmission and turn-off radio during inactive state[11].

Cluster structure helps in avoiding overlapping active parts of interfering nodes and multiple paths allowed overcoming single node failures, which effects network performance[11].

Protocol reduces the no. of packet losses and end-to-end delay. Also leads to energy saving by a reduction in a number of transmissions that occur at MAC layer. While the protocol is robust under complex interference patterns but it needs closer integration between IEEE 802.15.4 and RPL for achieving significant results[11].

F. ER-RPL: Energy-Efficient Region-Based RPL

ER-RPL[12] uses the subset of nodes for the discovery of route in comparison to traditional route discovery where all nodes used for route discovery, which results in high energy overhead but using only a subset of nodes allowed to minimize energy consumption. In addition, route discovered is near to optimally reliable.

ER-RPL is hybrid of reactive and proactive protocol that uses region information to help it in communication (P2P) and works in a decentralized way so it can support scalability. It is designed with support for generic-traffic with P2P route discovery and R2R (region-to-region) routing without the support of the route-discovery[12].

PDR increases by 150% and close to P2P RPL with symmetric links thus show the ability of ER-RPL to deliver near-optimal results while using the only subset of nodes for route discovery. Also by using route discovery, which is based on region information, ER-RPL is better in performance than P2P-RPL (with asymmetric links) by 10% because PDR degrades in P2P-RPL due to temporary DODAG is rooted at the source node which is not optimal for traffic under asymmetric links. While ER-RPL makes the temporary-DODAG rooted at the destination node, which helps to find the best path from source to destination. ER-RPL achieves 60% lesser control overhead when compared to P2P-RPL because destination nodes receive few packets only. In addition, ER-RPL achieves 60-66% energy conservation compared to RPL due to longer routes in RPL and bottleneck (root) as more and more traffic flows through root node. A significant difference from P2P-RPL due to frequency's differences in control messages of ER-RPL and P2P-RPL and number of successfully delivered packets is less in case of P2P-RPL (asymmetric links). The average hop count of P2P paths selected by ER-RPL is closer to P2P-RPL. Control overhead in ER-RPL is 59% - 66% lesser than P2P-RPL in case of both symmetric and asymmetric links. However, it is limited to static networks and assumes that there is enough buffer space available[12].

G. HECRPL: Hybrid, Energy-Efficient, and cluster-parent based RPL

HECRPL[13] is a routing protocol aimed at achieving energy-efficiency and reliability simultaneously. It uses top-down approach for selection of optimal-cluster parent set (CPS) which helps in energy conservation and benefits from the path diversity. Coordination among nodes in CPS based on overhearing which helps to reduce numbers of duplicate packets. Residual energy and lossy nature of wireless channel considered for assigning priority between candidate parents in CPS. In addition, HECRPL uses an efficient workload sharing approach, which uses dynamic update approach to updates the priorities of nodes in forwarding sets, which results to achieve fairness and extends the lifetime of the network. It also provides an efficient scheme for lost packets recovery. Transmission power is tuned to improve saving of energy and increase network capacity, which further increases spatial reuse and leads to better routing decision. Also as compared to traditional clustering protocols, which fails in case of failure of cluster heads, it uses multiple paths for robust performance. The author also designed and developed the CRPL but HECRPL differs from CRPL by using new energy-efficient routing metric for optimal CPS selection, which considers energy cost and lossy-nature of wireless networks, refinement of power levels, dynamic update procedure for topology and its maintenance and joint assignment of priorities. CFM (cluster-formation) message is introduced which helps in the propagation of node cost and network topology maintenance in HECRPL. In addition, the distance between nodes estimated using Received Signal Strength Indicator (RSSI) values.

HECRPL have more numbers of alive nodes than RPL as the rate of alive nodes starts from 87% and drops to 50% as traffic flow increases. The decrease in rate is due to more numbers of packets delivered than RPL in the same time of network working, which results in more energy consumption and thus causes some nodes to die, but HECRPL still maintains connectivity. Energy conservation is up to 40% in starting but as traffic flow increases and more data packets delivered, nodes tend to consume more energy. HECRPL effectively delays the time to die for the first node by 46% - 25% compared to RPL as traffic flow increases. Performance of HECRPL is 46% -25% more than RPL as traffic increases. HECRPL shows improvement in reliability up to 85% to 50% compared to RPL but performance decreases as traffic flow increases. HECRPL significantly delays the node's death and provide improved network connectivity and overall better network performance. As initially, PDR of HECRPL is better but on increase of traffic flow PDR decreases for both HECRPL and RPL, but HECRPL still works better than RPL as more number of packets delivered while also maintaining connectivity and significant energy conservation also[13].

ISSN: 2454-4248
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The spatial feature is not properly utilized due to timer-based priority scheduling for CPS coordination and efficient load sharing scheme is required to handle congestion. In addition, the author suggested the use of network coding for further improvements for protocol[13].

H. E2HRC: Energy-efficient heterogeneous ring clustering routing protocol.

E2HRC[14] routing protocol, uses ring domain as communication topology with each ring having equal area. This protocol tries to solve RPL's energy balance problem by using clustering based algorithm and event-driven cluster head rotation. A newly designed clustering information announcement message and clustering acknowledgment message are used. Ring domain communication routing based on the topology-control model used in the network, which consists of nodes divided into levels based on positions in the network. Also, ring domains divided based on levels. Clustering algorithm used for division of the network into heterogeneous clusters, according to node's residual energy and node's relative position in the cluster. To balance energy consumption and prevent energy hole, a combination of heterogeneous-cluster and cluster head rotation mechanism is used. E2HRC routing algorithm uses backbone routing mechanism, which works by selecting optimal relay node considering optimal-direction angle, the node's residual energy and a minimum number of hops.

E2HRC achieves balance in energy consumption as after routing establishment, nodes dynamically adjust to the transmitting power by the next hop node in their routing information when they have to transmit the data packets. E2HRC efficiently balances the network and decreasing energy consumption of nodes and number of control messages. Due to wider bandwidth in E2HRC, it helps in achieving less packet loss ratio compared to RPL. In addition, as no of nodes increases, E2HRC shows a decrease in packet loss ratio while RPL suffers from an increase in packet loss ratio. Due to optimal direction angle, E2HRC achieves more Packet delivery ratio compared to RPL. In addition, E2HRC reduces the number of control messages compared to RPL as time progresses[14].

Performance of E2HRC can improve by increasing packet delivering ratio as a number of nodes increases because PDR decreases as the number of nodes are increased, but still E2HRC works better than RPL[14].

TABLE I. COMPARISON BETWEEN CLUSTERING BASED ROUTING ALGORITHMS

Protocol	**Comparison Areas**		
	Problem area and technique used	***Outcomes***	***Shortcomings***
IRPL[10]	Works on energy balance by using an efficient-clustering algorithm and topology-control model, ring domain topology and optimal direction angle.	Reduces the number of control packets and achieves energy balance.	As the number of nodes increases the number of alive nodes decreases but it still works better than RPL
ORPL[8]	Works on improving reliability by using CPS (candidate parent set) instead of single parent and supports multiple paths.	Achieve better reliability than RPL and reduces energy consumption.	Due to single ACK, it suffers from the problem of corporation errors among parents.
ORPLx[8]	Works on reliability and improves ORPL by handling the issue of cooperation error among parents in ORPL.	Reduces the number of MAC layer retransmissions.	Slightly decrease in PDR compared to ORPL.
CRPL[9]	Works on reliability by using CPS with a better metric for CPS selection and top-down approach.	40% higher PDR than RPL, low delivery cost.	Requires additional memory due to use of local forwarding Table and protocol do not utilize the spatial feature.
RPL over IEEE 802.15.4 [11]	Works on energy efficiency by Integrating IEEE 802.15.4 and RPL, MAC modifications to support multi-paths, Converting cluster- tree into Cluster based DAG.	Fewer packet losses, less end-to-end delay, Less number of packet retransmissions at MAC layer.	Closer integration between IEEE 802.15.4 and RPL required for better results.
ER-RPL[12]	Works on energy efficiency by using only a subset of nodes for path selection and using region information.	PDR increases by 150% compared to RPL, less control overhead. 60-66% energy conservation compared to RPL.	Large Buffer Space requirement and limited to static networks.
HECRPL [13]	Works on energy efficiency and reliability by using energy efficient optimal CPS selection with workload sharing approach.	More alive nodes in the network, than RPL, better energy conservation, better PDR than RPL and provides better network balance.	Spatial utilization not properly utilized and congestion problem.

Protocol	**Comparison Areas**		
	Problem area and technique used	***Outcomes***	***Shortcomings***
E2HRC[14]	Works on energy balance by using Heterogeneous Cluster and Cluster Head Rotation Mechanism. Uses Communication Topology: Ring Domain.	Less packet loss ratio, improved PDR, less number of control messages, prevent energy hole.	PDR is better than RPL but decreases when a number of nodes increases in the network.

IV. Conclusion

This review focuses on clustering-based algorithm based protocols; these protocols provide better performance than RPL as clustering algorithms provide better performance and work well in lossy and resource-constrained environments. As we discuss in the review, each protocol is good in some areas but still, there are some areas of improvement. We hope we will be successful to provide a review for those working on RPL and this paper helps them in their research.

In future, using clustering based algorithms, suggesting an optimized RPL and developed using new or improved routing techniques.

Acknowledgment

I would like to acknowledge Director and Head of Department of Computer Science at Punjab Engineering College for providing the research facility for carrying out work.

I would also like to thank my fellow researchers (Ashima Khosla, Jinee Goyal) for their great assistance while researching and writing this paper. This research would have never been possible without them.

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