RPL for IoT – A Design Approach

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***Abstract*—** IoT is an interconnected network grid consist of different devices and other things that are related to human being. IoT is a dynamic global network infrastructure that have connected by unique devices through the internet. The devices are communicated via packet forwarding in low power lossy network through routing mechanism. RPL is a routing protocol which routes the packet in the network layer of IoT. This paper proposes a finite state automata of the routing protocol RPL and also discuss about the design elements of the protocol. Finite state automata describes the different parameters and factors that enhances the perfect routing in the LLN.

***Keywords*—** *—IoT, RPL, DAG, DODAG, Mobility models*

I. INTRODUCTION

A new evolution in modern day connectivity taking our world by storm. Anything that can be connected to the internet will make a digitalization era. Everything that are connected in internet world is simply coined as Internet of Things (IoT). IoT provide an advance level of services to the society, organization, home etc. Enhanced level of services are done with the help of IoT. Different things such as lighting system, vehicle, watch etc are fitted with embedded system, embedded processors, and information technology [1]. IoT is a giant network with connected devices. The IoT applications are smart home, smart health, smart car, smart devices etc. Figure 1 shows the abstract view of IoT Application scenario. These devices gather and share data about how they are used and the environment in which they are operated. It's all done using sensors, sensors are embedded in every physical devices.

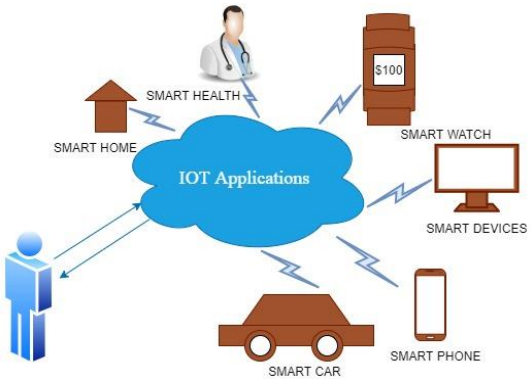


Fig1: IoT Applications

IoT consist of mainly three layers data link layer, network layer and session layer as in figure 2. In this paper we are focusing on IoT network layer and the protocols [3]. Thus it has some characteristics such as dynamic, self-adapting, self configuring, unique identity for the every devices, integrated to Information network. The network layer are capable of sending IP datagram from source to destination via internet. This layer takes the role of packet routing and host addressing. Hierarchical IP addressing scheme such as IPV4, IPV6 responsible for host identification.

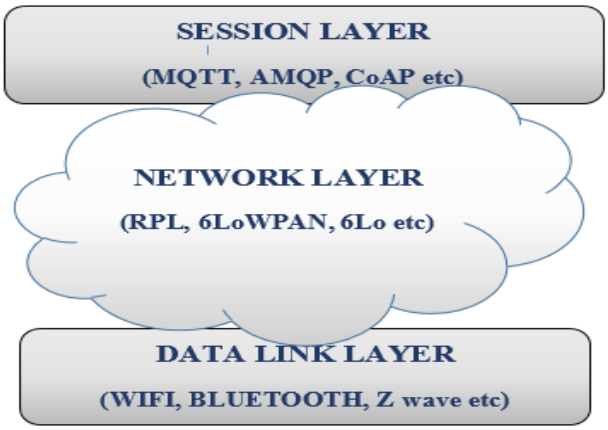


Fig 2: IoT protocol layer

The main goal of IoT is to enhance the efficiency, reliability, price and adaptability in a network. Most effective providers of IoT are the Wireless sensor networks (WSN) [23] [24] [25]. WSN has the application to sense several variables associated with the environment during the devices are inserted [26]. WSN are composed of different kinds of sensors as nodes, which is a special kind of LoWPAN (Low-power Wireless Personal Area Network).Lack of IP communication infrastructure in WSN and Internet limited the interoperability between them. To solve this problem there consist of several works dedicated to proposing a structure that provides use of IP over LoWPAN [27] [28].

In October 2004, IETF (Internet Engineering Task Force) proposed a working group named 6LoWPAN as a regular solution for the problem [29]. As in the definition of IEEE 802.15.4 radio, 6LoWPAN defines how to run IPV6 (Internet protocol Version 6) over low power, low data radio network. IETF working groups for 6LoWPAN ends in January 2014, after publication of its related RFC [30] [31] [32] [33] [34]

[35]. After that a new working group is emerged to routing in low power lossy network.

The sensor nodes are communicated in the LLN (Low power Lossy Network) via basic border router. For the communication it is important to deliver the packet to the destination with a best shortest route, needs routing mechanism. Procedure for routing mechanism are generally termed as routing protocol. Routing protocol has the power to transfer the packet in the network. Initial working group is RoLL (Routing over Low power Lossy Network) created in February 2008. It is created in the field of home automation [36], urban [37], industrial [38] and building automation [39] LLN. RoLL Working Group developed a standard routing protocol for LLN over IPV6 termed as RPL (Routing Protocol for Low power Lossy Network) in March 2012 [40].

RPL is a routing protocol used for packet routing across the internet. This paper focusing on the detailed study of RPL and proposes a design of its timed automata. The RPL has the highest path selection that impacts on the routing behavior. RPL is based on DODAG for LLN with IPV6 a standard for WSN [4] [2].

The rest of this paper organized as follows. Section II shows the literature survey, section III describe the overview of RPL, section IV elaborate the design elements of RPL protocol, section V Introducing the basic concept of timed automata, section VI present the timed automata for RPL, section, section VII concludes the paper and proposes a future work

II. LITERATURE SURVEY

Network layer has the responsibility to transmitting IP datagrams from the sender to receiver. Network layer has the function of host identification and routing of packet. Generally IoT network layer protocol classified as encapsulation protocol and routing protocol. 6LoWPAN [19], 6TiSCH [5], 6Lo [6] are the encapsulation protocols. Addresses of IPV6 are too long and that are not fit in IoT data link frames. IETF provide a set of standard for IPV6 datagrams to the encapsulation protocol. Routing means how routers are communicate with each other. It performs the traffic direction functions on the internet. In IoT routing protocol are implemented in IoT network layer. RPL is an open routing protocol for smart object network standardized by the IETF. This is designed to deliver the packet to the destination of a low powered lossy network. Generally RPL is termed as "Ripple" routing protocol for low powered lossy network [9].

In [10] the author have shown the related works for the RPL, also explained the working of the protocol. This included performance evaluation of RPL, such as power consumption, packet loss and packet delivery ratio. However the author cannot investigate the design of RPL. Until now Objective Functions is an open research problem. In [15] [17], the researchers proposes some solution for this, one of the method is Expected Number of Transmission (ETX). ETX needs to transmit the packet to the network by passing a particular path selection criteria in RPL. RPL limits the traffic in the network by minimizing the total ETX from the source to the DODAG root. This paper cannot focuses the design aspects of RPL. Another method is proposed in the paper [18], introduces OF0 (Object Function 0). It supported abstract information like rank and also not supported in link layer. It does not describe the each state changes of DODAG after the calculation of OF. Doesn't mention about the design perspective of RPL.

In [11] [16] author simulate and verified the protocol in contiki RPL simulator. Along with other parameters they verify the how OF impact on the average number of hops and average node energy. The result is similar to computing the rank that it is insignificant because of the parameter specification regarding the design. Not mention about the RPL design aspects.

In [12] author have provided the initial simulation of RPL performance. The traffic patterns and size of network are still limited. RPL to meet different requirements in specific application scenarios [13] [14]. This is also try to find RPL features in Contiki not in the real platform.

In this paper [20] introduces Mobility enhanced RPL (MERPL) a next level routing method to enhance RPL, which balances the traffic over the network. It ensures the stability of route in the network than RPL. However, authors don't mention about the state machine of RPL.

The authors in [21], proposes a unique method to improve the RPL mechanism is Co-RPL. The Corona mechanism is used for the positioning the nodes in the network. This keeps the position of the DAG root to get the movement of nodes for the efficient routing. Nevertheless, finite state machine of RPL is not mentioned in this paper. In [22], the authors enhances the features of RPL like mobility, rank etc. This paper presented some schemes and analyzed the impact on the LLNS requirements, but not referred about the each state transition of RPL working.

III. RPL OVERVIEW

RPL is a hierarchical tree based network protocol consist of source based distance-vector routing mechanism. RPL is meant to work on top of IEEE 802.15.4 PHY and MAC layers [44]. The RPL provides a specific routing mechanism for low power lossy network [42]. RPL supports three kinds of traffic inside LLN such as point to point, point to multi point and multipoint to point. The protocol uses the trickle timer mechanism, where periodically send measurements to the root in the DODAG. Whenever the default routes are inaccessible in the network, it automatically configured with alternate routes. Auto-configuration guaranteed by Neighbor Discovery (ND) mechanism. Self- healing is a property of RPL because it has the capacity to hold more than one parent per node. The protocol detect and avoid loop occurrence in the network by using the global and local repair methods. It has multiple edge routes so that it balance the availability and transparency of the route in the network [11] [43]. The important features of RPL protocol are listed in the table 1[25].

RPL is based on hierarchical based DODAG (Destination Oriented DAGs). DAG root is simply act as a gateway to the Internet. One or more DODAG consist of a RPL instance are identified by a unique ID, called RPLInstanceID. The LLN consist of a group of RPL instances simultaneously and they

are independent. A RPL node may join numerous RPL cases, yet should just have a place with one DODAG inside each case. Every node in the DODAG are assigned with rank. Rank are calculated using the OF. The rank carefully increments the downstream way of the DAG, and carefully decrements the upstream way [25]. Figure 3 illustrates RPL instance with various DODAGs.

DODAG are build using objective function and a set of metrics. The objective function is used to compute the best path by operate on a combination of metrics and constraints. This function is used to dictate the rules rather than specifying the constraints. Objective function help as to decide whether we are near to the root or away from it. This is designed by the programmer.

In RPL network topology is construct based on the object function which selects preferred parent from a stable set of list on a path towards the DODAG root. Object function is responsible to translate one or more metrics into rank and also select and optimize the path in the DODAG. The object function defines the how to calculate rank dependent on specific directing measurements (for example delay, interface quality, availability, and so on).

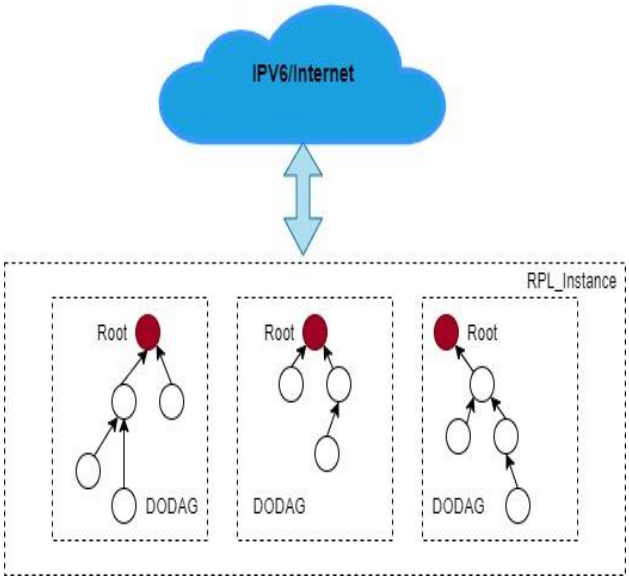


Fig 3: RPL instance with various DODAGs

A. RPL Control Messages

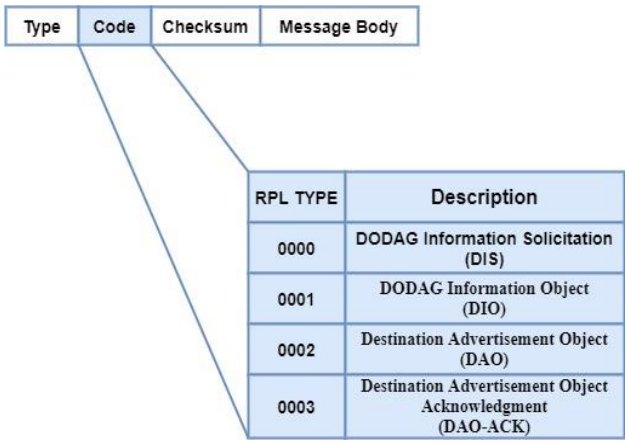
RPL working is based on the 4 control messages used to communicate the new node to the already existing node. DIO (DODAG Information Object) message send from the sink node to source node, whether they are interested to join the exciting DAG. DIS (DODAG Information Solicitation) message is used to join to DAG by a new node. DAO (DODAG Advertisement object) is send by the child to the parent that they are ready to join the DAG. DAO-ACK it give an acknowledgement to the new node that it being the part of the DAG as in figure 3. In detail,

1) DODAG Information Object (DIO): This message is used to rebuild the DODAG structure and always maintain a route towards DODAG root from every node in the network. Also has the permit to find RPL instance, become familiar with its configuration parameters, select a DODAG parent set, and maintain the DODAG [11] [43].

2) DODAG Information Solicitation (DIS): It is utilized to send request to the RPL node to get DODAG Information Object (DIO). The DIS can have the permit to check neighbor nodes from different adjoining DODAGs [11] [43].

3) Destination Advertisement Object (DAO): It is used to maintain the downward routing and record the path information of the nodes visited along the upward path. Except DODAG root, every node sent DAO messages to construct the routing table. Routing table contains the entry list of parent and child details. [11] [43].

4) Destination Advertisement Object Acknowledgment (DAO-ACK): It is issued to acknowledge to the recipient of DAO message by sending as a unicast information. [11][43].



RPL TYPE	Description
0000	DODAG Information Solicitation (DIS)
0001	DODAG Information Object (DIO)
0002	Destination Advertisement Object (DAO)
0003	Destination Advertisement Object Acknowledgment (DAO-ACK)

Fig 4: RPL Control Message

B. Construction of DODAG

The construction of DODAG is based on the Neighbor Discovery (ND) procedure, which consist of two main operations. (i) Multicasting of DIO, (ii) unicasting of DAO. DIO control message build down routes from the DODAG root to the client node whereas DAO control message are used to construct the upward routes from them client node to the DODAG root. When a DODAG root sends a DIO message, which contains the information like the DODAG ID, Rank and Object Function. The node in the listening vicinity will receive this message [43].

If a node ready to join the DODAG and receives a DIO message. It will updates its routing information by assign the DIO sender address to the routing table. Then it calculate the rank with respect to the object function. After that check whether the rank of the parent is less than that of the client node, if it true then it transmit a DIO message with updated rank information. The node chooses the most preferred parent from the parent list [43].

If a node already exist in the DODAG and receives a DIO message, it has three method to operate the message (i) remove DIO message with respect to the RPL requirement (ii)

process the DIO message and maintain its position (iii) updates its position by obtaining the low rank based on the object function. Whenever a node is removed from the DAG or changes its rank. Then it modify the routing table and recomputed the new routing loops [43].

The DODAG construction methods are generally classified into two routing types they are (i) Upward routing (ii) downward routing. The figure 5 shows the upward routing steps. As shown in the figure 5(a) consist of 4 routers with a source root. Initially set the rank of source root as 0.Source root broadcast a DIO message carrying the information such as RPL instance ID, DODAG ID, Rank etc to its neighbor nodes as in figure 5(b). The node A & B in the listening vicinity hears the DIO message set the source node as its parent and join the DODAG and updates the information. The nodes which will be the part of the DODAG means A & B also broadcast the DIO to its neighboring nodes as in the figure 5(c). The node C & D in the listening vicinity hears the DIO message and select the parent with least rank as its parent and join the DODAG. Transmission of DIS message is also be a part of upward routing.

Downward routing is constructed using DAO packets. When receiving the roots DIO packet, A & B returns a DAO packet to the source root as in figure 6(a). When the source root receives the DAO message, the source root adds A& B's information to its routing table and return a DAO_ACK messages as in figure 6(b). Similarly every node processes the DAO information, it sends update information to its parent and returns a DAO_ACK message to its children nodes. Finally root node obtains all the information of the entire DODAG. The figure 6(c) shows the final DODAG. As the figure 7 shows the case of new entry to the existing DODAG. E broadcast DIS message to solicit to join the DODAG. The node B hears the message and returns a DIO message as in the figure 7(a). At this moment the DODAG's upward routing is established. Figure 7(b) shows that E sends a DAO message to B and returns a DAO_ACK. Now the downward routing is established and a new DODAG is formed.

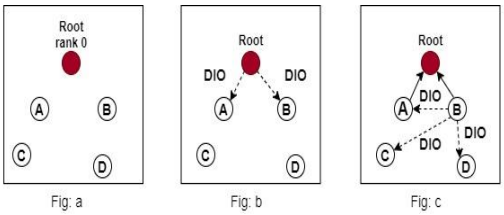


Fig 5: upward routing

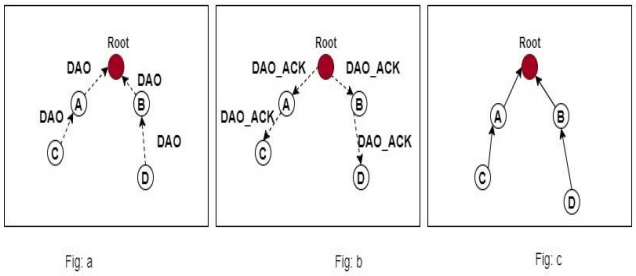


Fig 6: downward routing

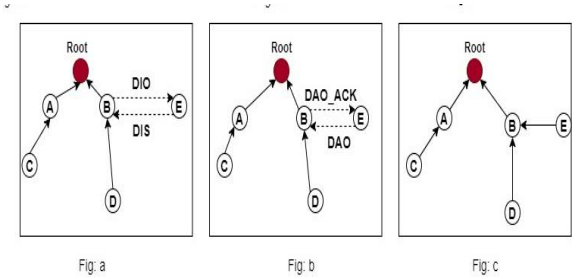


Fig 7: DAG topology changes when new node enter

C. *Trickle Timer*

RPL timer mechanism is called as "Trickle Timer". As the name implies RPL router drizzles the DIO message every so often, except from limiting the infinite flow by enabling the router to determine the redundancy of DIO transmission.

When a RPL router transmits a DIO message, it has two possible scenarios may occur. (i) Either every neighbor router that receives the message and finds the rank, DODAG ID, etc. Also take some decision regarding the information that gets from the findings. (ii)If the information is out-of-date, then it upgrade the information based on received DIO message content.

TABLE 1: Features of RPL

Properties	**Explanation**
Auto-configuration	As in Internet Protocol V6 neighbor discovery mechanism
Transmitting modes	Storing and Non-Storing mechanism
Self-Healing	Able to adapt topology changes
Loop Avoidance and Detection	Local and Global repair mechanism
Independent and transparency	Operate over multiple link layers
Multiple edge routers	Higher availability and load balancing

IV. DESIGN ELEMENTS

For the design of RPL needs 5 essential criteria they are:

A. *Service Specification*

The purpose of this protocol is to deliver or route the packet in a low power lossy network, which contains a large set of nodes with low memory power and energy. The networks are connected with lossy links, low data rate and sensitive to low packet delivery ratio. Thus RPL fulfill the low power lossy networks requirements more precisely. The traffic patterns are not only point to point but also multi point to point and point to multi point.

B. Assumptions

Environment of the protocol consist minimum of three users for the service of packet delivery and also contains a transmission channel. The three users are source node, destination node and at least one intermediate route.

C. Service Specification

The protocol vocabulary defines the type of message used in RPL protocol are:

V= {DIO, DAO, DIS, DAO_ACK}

1) DIO: A source node sends a DIO message to an existing DODAG to join the DODAG and also used to rebuild the DODAG by broadcast towards the root.

2) DAO: The message send by the every node except DODAG root, to rearrange the routing table and prefixes the child and parent.

3) DIS: This message is used to request to get DIO and also to test the neighbor nodes to join the DODAG

4) DACK: Acknowledgement message to the reply of DAO message

D. Message Format

RPL control message consist of an ICMP V6 header followed by a message body. The message body comprised of a message base and possibly an option.

E. Procedure rules

Procedural rules for RPL are as follows:

- Root broadcast the DIO message to the nearby nodes.
- The node in the listening vicinity receive the message and process (by means of OF, DAG characteristic, path cost) then send a DAO message as the reply.
- When the root receives the DAO it acknowledge with DAO_ACK message for the node who sends the DAO.
- If a node or a LLN wants to join the DODAG, it solicit the grounded DODAG by sending the DIS message to the root.
- DODAG will upgrade at an interval of time by sending the DIO message to every node in its own id.

V. TIMED AUTOMATA

Timed automaton is a real valued finite set of clocks. It is used to modal the real time system. It defines the state-transition graph with timing constraints contain finite set of real valued clocks. Timed automaton can be represented in a 6 tuple format as A= {L, L^0, Σ, X, I, E}. Set of location is represented as L, L^0 is the initial location ($L^0 \subseteq L$), Σ is the set of labels, X represented as the set of clocks, I is the mapping function which maps location s with some clock constraint Φ(X). E is the set of switches or edges [41].

VI. TIMED AUTOMATA FOR RPL

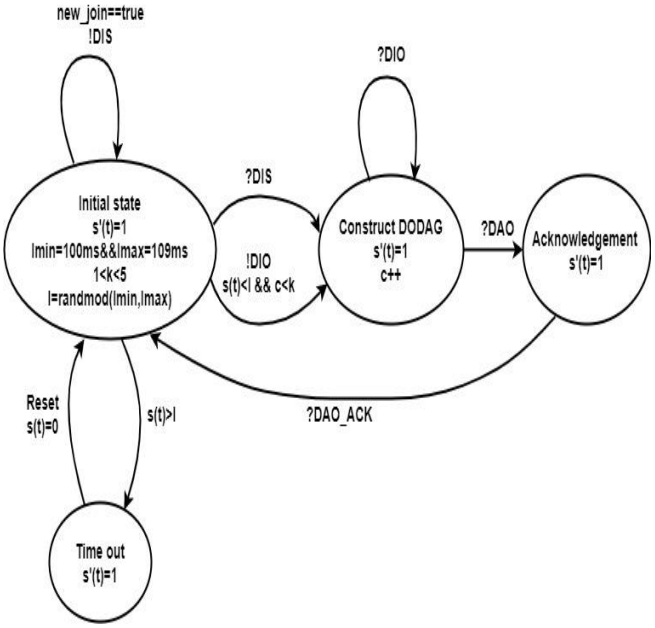


Fig 5: Finite state automata of RPL

The above figure 5 shows the finite state automata of RPL. The automata contains mainly four states abstracted consist of four constraints. The four RPL state are initial state, construct DODAG, Acknowledgment, Time out. In the initial state the value of Imin and Imax are 100ms and 109ms respectively, value of k is selected between 1 and 5, value of trickle timer I is bounded by the interval [Imin & Imax] with respect to the clock variable t. Construct DODAG state is abstracted with different levels of calculation and decisions such as parent selection based on quality of links or hop count, the advertised OF, path cost, rank etc. The node with lower rank is considered as candidate parent. After updating the routing table the node sends an acknowledgement to every node in the DODAG. If I expires then time out state will occur, it resets the essential variable and activate the transmission without any trouble.

The constraints are regards with the sending and receiving of different control messages such as DIO, DIS, DAO, and DAO_ACK. The nodes in DODAG emitted DIO messages periodically with a periodic timer t with respect to trickle timer I. Whenever the t expires a DIO message is sent if the counter is less than the redundancy constant k. The value of c is incremented by 1, whenever a node hears a DIO message that is consistent. When I expires and node is consistent, I and t are reset to new value. When a node or LLN wants join the DODAG, it may multicast a solicit message called DIS. So that other nodes hearing the DIS start sending DIO message and newly arrived node can join the DAG. DAO, the multicast advertisement option for hop reachability and unicast reachable prefix to their parents in the DAG to advertise their address and prefixes. The nodes that receives the DAO will update the routing table and sent an acknowledgement DAO_ACK.

VII. CONCLUSION AND FUTURE WORK

This paper describes about the routing mechanism in the network layer of IoT architecture. It provides a detailed description of routing mechanism of RPL. Also discussed about the design elements of the RPL protocol. A finite state automata is proposed in this paper with respect to various factors and parameters that depends on this RPL protocol.

Theoretical verification using the mathematical model and real time verification using the promela model is considered as a future work of this paper.

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