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Congestion-Aware Routing Protocol for 6TiSCH Wireless Sensor Networks

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Abstract — **With the help of Wireless Sensor Networks (WSN) and the evolution of various applications for Internet of Things (IoT), different devices require low power operations, less latency, lower delay and better end-to-end reliability. After the evolution of IEEE 802.15.4 standard and IPv6 addressing schemes, there is a demand for designing routing protocol for 6TiSCH WSN which can facilitate efficient communication. RPL is IPv6 routing protocol for low power and lossy networks, proposed by Internet Engineering Task Force (IETF) and routing over low-power and lossy networks (ROLL) working group. RPL is standard IPv6 routing protocol for IoT environments which need to be improved to achieve more routing efficiency and improved packet delivery ratio (PDR). Congestion control needed to be considered for design of routing protocols for WSN like RPL so that the routing process can be optimized. In any low power and lossy network (LLN), congestion may play an important role for network lifetime reduction. In this paper, a new improved RPL has been proposed for congestion control and load-balancing in case of 6TiSCH Networks.**

***Keywords* — RPL, congestion control, load balancing, Wireless Sensor Networks (WSN), Energy Optimization.**

I. Introduction

Wireless Sensor Networks (WSN) are known to be susceptible from different energy consumption issues and enormous algorithms are devised so far for the escalation of lifetime in the sensor nodes and overall network environment [1]. IoT devices can be energy-constrained with less possibility of energy harvesting, while energy consumption is primarily due to radio communications [2]. As a counterpart, energy is wasted by transmission of all types of data, protocol overhead, and communication patterns. In this sense, the scientific community identified the development of energy-saving communication protocols for an industrial IoT, due to some challenges in providing the highest level of reliability for the devices deployed with unreliable wireless technologies [3]. Recently, control regulatory and real-time monitoring systems become crucial in running and maintaining industrial applications. However, the cost of procurement and maintenance of such a wired network makes it less feasible if implemented on a very large-scale industrial setting [4]. Consequently, this increased the demand on having wireless sensor networks on their industrial applications. Furthermore, it motivated many researchers to focus on creating, optimizing and reusing existing wireless protocol standards to come up with cost-effective, low-powered, reliable, and secured wireless networks [5]. As a solution, the IEEE 802.15.4 protocol has been designed for low-data rate wireless networks with energy efficient operation [6]. The Internet Engineering Task Force (IETF) formed working groups of researchers to create protocols which will be a standard for low-powered, multi-hop wireless personal area networks (WPANs) running in industrial applications. These protocols are the IETF Constrained Application Protocol (CoAP), IPv6 over Low power Wireless Personal Area Networks (6LoWPAN); Routing Protocol over Low power and Lossy Networks (RPL), IETF 6top and the IEEE802.15.4e TSCH [7-9]. The IEEE 802.15.4e is the amendment of the IEEE 802.15.4 for low power consumption and high reliability [10]. Time Slotted Channel Hopping (TSCH) is one of the MAC modes supported by this protocol [11]. TSCH is a reservation-based medium access technique, which is a hybrid of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) [12]. TSCH combines time slotted access with multiple channels and channel hopping capability. This technique uses time synchronization of nodes in the network in order to achieve low-power operation, and channel

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hopping for high reliability [13]. All nodes can synchronize and resynchronize their clocks with the TSCH network either through Acknowledge-based or Frame-based. The overhead of this synchronization is very low. When the new MAC based framework incorporated in IPv6-based LLN protocols, a new IETF working group has been defined, namely "IPv6 over the TSCH mode of IEEE 802.15.4e" (6TiSCH). The need for standard protocols for wireless networks led the IETF 6TiSCH Working Group to create an IPv6-enabled multi-link subnet with industrial-grade performance called 6TiSCH [14-17]. These protocols are linked on top of the other to form the 6TiSCH communication stack. 6TiSCH is a standard architecture for Low-power and Lossy Networks (LLN), specifically Internet of Things (IoT) [18]. For the IPv6-compliant Low-power and Lossy Networks (LLNs) with large multi-hop resource based on IEEE802.15.4 radios, novel protocols have been standardized within the IETF. IEEE802.15.4e Time-slotted Channel Hopping (TSCH) MAC amendment can be used for reducing idle-listening. 6TiSCH stack can be considered as better solution for optimization of routing solutions with congestion control mechanism [19]. ZigBee Alliance introduced a communication stack for the formation of wireless sensor networks [20]. One of the advantages of this protocol stack is that it operates on top of IEEE 802.15.4 compliant devices [21]. The IETF 6top and IEEE802.15.4e in TSCH mode define the link layer. Network discovery and routing was achieved through 6LoWPAN and RPL [3, 22]. 6TiSCH can operate on top of IEEE 802.15.4 low power radios. The IETF 6top and IEEE 802.15.4e TSCH makes up for the link layer of 6TiSCH. For the MAC sublayer, 6TiSCH uses IEEE 802.15.4e in TSCH mode [23]. However, IEEE 802.15.4e only indicates how each node will execute the schedule for communication in the network [24]. It is not meant to specify how the communication schedule will be built and managed; rather to match that schedule with the routes specified by RPL. The IETF 6top fills in this role. 6top builds and manages the TSCH schedule for the IEEE 802.15.4e. It achieves this through gathering of existing and working node links from the MAC layer for the allocation priorities of the nodes within the clusters of the network [25]. While 6top is doing this, the Path Computation Element (PCE) and/or RPL also makes use of this data to create optimal and redundant tracks for the nodes of the network. Tracks are multi-hop paths between source and destination nodes [26]. Routing computation can be achieved in a centralized mechanism using a Path Computation Entity (PCE). A decentralized approach with the use of RPL and a resource reservation protocol can considered to be a better solution [27]. The centralized and distributed mechanism can also be integrated together without conflict [28]. The rest of the paper is organized with following sections. In section II, different relevant literatures discussed. In section III, the experimental setup and algorithm is explained. In section IV, shows the performance with simulation results and analysis. Finally, the conclusion and recommendations for future work discussed in sections V and VI, respectively.

II. Literature Review

The most significant challenges in the design of Routing protocols using IPv6 depends on the survival of nodes in the networks and limiting the use of the batteries of each node [1]. Using IPv6 without compressing of header may lead to the consumption of more energy and shorten the lifetime of nodes in WSN [14]. The use of compression algorithm for the applications of WSN using IPv6 can help to minimize the energy consumption and maximize the lifetime with the use of inter-cluster routing. The algorithm with separate inter-cluster and intra-cluster routing can be useful for increasing energy efficiency in case of the use of IPv6 addressing [1, 15]. The difference between traditional Wireless Sensor Networks (WSNs) is that it has stringent requirements in terms of energy efficiency, reliability, and end-to-end latency. These led to the further development of the suitable protocols to be deployed together with low-powered radios to operate in extreme and harsh conditions in the industrial setting [8]. These led to the further development of the suitable protocols to be deployed together with low-powered radios to

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operate in extreme and harsh conditions in the industrial setting [4]. Many researchers attempted to evaluate and optimize the performance of wireless sensor network protocols with concerns on real-time aspects aside from energy efficiency. The modified protocol used GTS mechanism as their scheduling mechanism [11]. Performance metric used was worst case end-to-end latency, which depend on the number of symbols transmitted and data rate used. Congestion control is a critical design issue in WSNs classified into two categories [17]. One is defined as node-level congestion caused by buffer flow and another category can be defined on link-level congestion caused by distributed MAC layer protocols. The distributed MAC protocols allow the sensor nodes to compete to obtain the opportunity to seize the channel which will introduce more collisions and congestions caused by buffer overflow in node-level congestion. To reduce the congestion, these works utilize the traffic control as the major technique. Wan et al. (2003) provided a comprehensive review on traffic congestion and proposed a scheme to avoid congestion based on congestion detection, hop-by-hop backpressure and multi-source regulation. The receiver monitors the traffic and the current buffer occupancy. The traffic information will be sent through backpressure messages to upstream neighbors to limit the packet sending rate. Furthermore, the multi-source regulation provides a congestion control in the end-to-end communication. Hull et al. (2004) proposed a mechanism named Fusion based on three congestion mitigation techniques, including hop-by-hop flow control, limiting source rate, and prioritized medium access control. These three congestion techniques could mitigate the congestion by preventing the transmission to the congested nodes. Then, Chen and Yang (2006) proposed a congestion-avoidance scheme based on light-weight buffer management. The basic idea of the scheme is based on the hop-by-hop flow control. Performance of IEEE 802.15.4e protocol was evaluated through network formation. Node's joining time was the metric used in the evaluation. The network formation involved random-based advertisement algorithm, with Discrete Time Markov Chain as the node connection process model. The main idea of this research is to reroute the packets to bypass the congestion area. Ren et al. (2011) proposed traffic-aware dynamic routing algorithm to route the packets in and around the congestion area and scatter packets to light loaded relay nodes to alleviate buffer flow. Many researchers attempted to evaluate and optimize the performance of wireless sensor network protocols with concerns on real-time aspects aside from energy efficiency. These works used various evaluation techniques ranging from analytical computations, simulation experiments, and experimental lab measurements. Duquennoy et al. [13] proposed an autonomous scheduling algorithm for distributed and centralized schemes named as Orchestra which does not require any signaling overhead even locally among neighboring nodes where each and every node can autonomously decide its own schedule for any type of network traffic. Morell et al. [16] proposed a distributed scheduling algorithm in which each node reserves required bandwidth along the path to the sink after formation of the topology using the Resource Reservation Protocol (RSVP) and Generalized Multi-Protocol Label Switching (GMPLS). After this bandwidth reservation, the Completely Fair Distributed Schedule (CFDS) for the TSCH schedule of network nodes for back to back receptions and transmissions of different types of communication packets. Domingo-Prieto et al. [17] proposed a distributed scheduling algorithm based on proportional-integral-derivative (PID) controller. The proposed algorithm uses pairwise communication between neighboring nodes and aims at stabilization of schedule under varying application requirements. Papadopoulos et al. [18] developed Leapfrog Collaboration (LC) proposed a new communication mechanism for improving the reliability of 6TiSCH wireless networks. LC exploits path diversity through parallel transmissions over two paths with promiscuous nodes for overhearing between the paths. Theoleyre and Papadopoulos [19] addressed the issue of 6TiSCH wireless networks for traffic isolation with the exploitation of 6TiSCH networks. Municio and Latré [15] proposed DeBraS algorithm which is broadcast-based decentralized scheduling with reduced collisions and improved scalability. All centralized scheduling approaches are used to evaluate the performance of 6TiSCH during

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network formation like TASA [20] and AMUS [21]. The protocols like RPL with 6top and IEEE 802.15.4e in TSCH mode shows a better result with IPv6 addressing in congestion aware networks [29, 30]. Performance metrics included end-to-end latency, throughput, and packet loss for the measurement of the routing efficiency of various routing protocols for IPv6 Networks in WSN.

III. ROUTING FOR 6TISCH

Wireless Sensor Networks have found thousands of applications to simplify the management of complex problems. Energy conservation in wireless sensor nodes is prime concern to engineers in most of its applications. This becomes important as increase in the network life-time depends mainly on minimizing the energy consumption in sensor nodes. Main challenge in WSN is to design routing algorithm with minimum energy expenditure. Different researchers proposed many such algorithms and hierarchical cluster-based routing protocols are efficient for WSN which can minimize energy consumption but so far none of them was modified with IPv6 and dual addressing schemes. This thesis has proposed such protocol using IPv6 to improve the WSN performance. The issues pertaining to design the topology with certain number of base station and their position in the network is due to location and mobility factor. The energy minimization also depends on path loss along with the position of deploying sensor nodes and estimation of energy due to mobility of nodes. Clustering techniques are important to save energy in the network and k means clustering technique is used for the formation of the clusters in WSN. The new routing technique has been proposed using IPv6 to minimize as well as to balance the energy consumption among the nodes when there is a growth in the network and the topology formation also modified due to scalability in the network. RoLL group for routing over low-power and lossy networks investigated the use of other extensions of those protocols, such as [13–16]. RPL is a distance-vector routing protocol that forms the LLN as a Destination Oriented Directed Acyclic Graph (DODAG) [14]. Fig.1 explained the formation of DODAG. All data are destined to one sink node, i.e., the DODAG root. The RANK is a number that defines the distance of each node relative to the DODAG root. RANK strictly increases in the down direction and strictly decreases in the up direction, with the DODAG root having the lowest RANK. WG defined methods for IPv6 routing with resource constraints in low power and lossy networks which is proposed by the ROLL WG with time-slotted channel hopping [17]. The proposed routing algorithm is for unicast, anycast and multicast routing environment with multipath routing support so that load balancing can be possible in the network. IETF standardization body also proposed another routing protocol with IPv6 based multi-hop Low-power and Lossy Networks (LLNs) with the specification from three different IETF working groups (WGs) with three layers of stack.

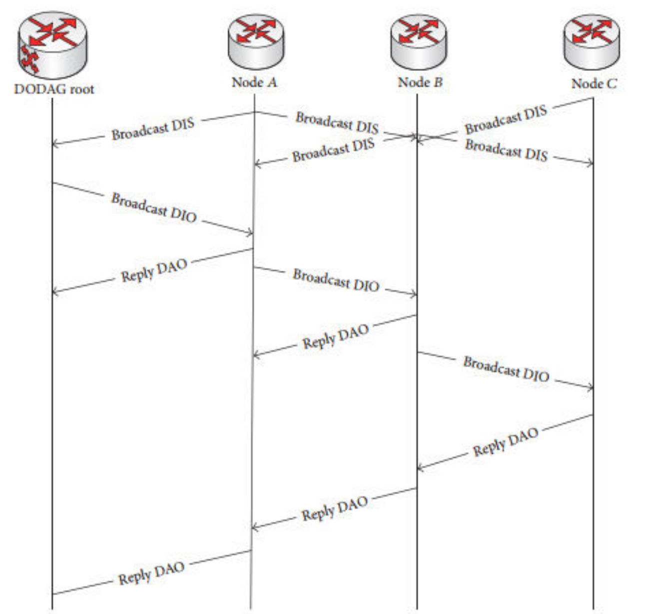

Fig. 1 (a). DODAG Nodes

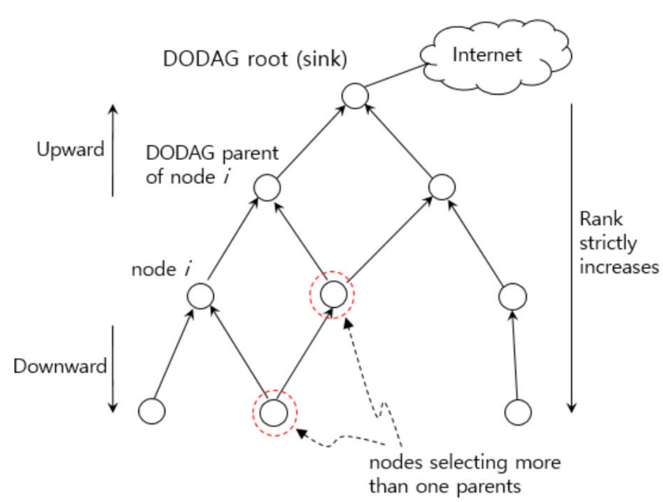

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Fig. 1 (b). DODAG Formation

RPL [17] for low-power and lossy networks (LLNs) is a proactive, distance-vector routing by high loss rates, low data rates, and instability. In the routing protocols like LLNs, routers can operate with constraints of processing power, memory and energy. Congestion causes packet losses and delay in the first place. Packet losses in LLNs can be another issue for reliability and robustness of the applications. In case of end-to-end congestion control and packet recovery the upper layer protocols are not capable of handling routing issues due to resource limitations. The 6LoWPAN protocol is used in delivering IPv6 packet over IEEE 802.15.4 based wireless sensor networks (WSNs). In 6LoWPAN [3], adaptation layer is introduced in the protocol stack so that routing can be performed either in the adaptation layer, called mesh-under routing (MUR), or in the network layer, called route-over routing (ROR). To deliver an IPv6 packet over a WSN, the packet has to be divided into multiple fragments, with each being carried in an IEEE 802.15.4 frame, due to the small payload of an 802.15.4 frame. Thus, MUR exhibits the drawback of low packet arrival rate (PAR) when delivering an IPv6 packet over a route consisting of multiple unreliable links in the WSN because the destination node cannot assemble the original IPv6 packet if any fragment of the packet is lost over any link. Cross-layer design and optimization is a new technique, which can be used to design and improve the performance of wireless networks. The central idea of cross-layer design is to optimize the control and exchange of information over two or more layers to achieve significant performance improvements by exploiting the interactions between various protocol layers. Non-uniform energy depletion due to unbalanced workload distribution and wastage of energy due to congestion will shorten the overall network lifetime. Load-balancing can be utilized to alleviate congestion. RPL supports multipoint-to-point, point-to-multipoint, and point-to-point traffic in any directions of the traffic patterns. Typical application scenarios such as monitoring in LLNs require multipoint-to-point traffic flows from the sensing devices to the central control point. Sensor networks are gradually moving towards full-IPv6 architectures and play an important role in the upcoming Internet of Things. Some mission-critical applications of sensor networks will require a level of reliability that excludes the presence of single points of failure, as it is often the case today for the gateways connecting sensor networks to the Internet. Applications such as actuation and selective sensor queries generate point-to-multipoint traffic flows which need downward routes. RPL is based on LLNs comprising of various nodes can envision diverse point-to-point IoT applications for the devices interacts among each other using IPv6 address in LLN work in all IEEE802.15.4 based networks and have been included in the ZigBeeIP stack [12], as shown in Fig. 2.

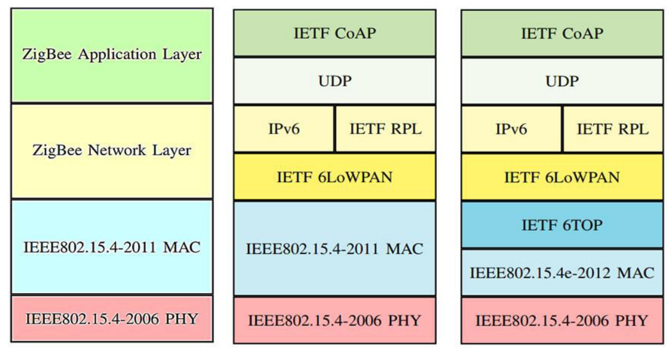

Fig. 2. ZigBeeIP and 6TiSCH

6LoWPAN gives a great opportunity for sensor networks to communicate with the Internet using IP. However, it's difficult for the 6LoWPAN sensor networks to be operated from the Internet directly. In this paper, an access gateway and sensor nodes based on 6LoWPAN are designed and constructed to make the interconnection feasible. This solution allows legal Internet IPv4 client to access and control each specific sensor nodes using IPv6. Furthermore, it enables different sensor networks to exchange information through a 6to4 tunnel implementation. Besides, the performance of the WSN has been evaluated and analyzed. The experimental results show that the interconnection between IPv6 WSN and Internet is successful and reliable. In this paper, RPL-6LBR and 6LoWPAN introduced to address the routing for 6TiSCH with the comparison of existing standards may be leveraged to enable redundant border router synchronization, while identifying certain of their

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shortcomings. The proposed RPL-6LBR tested in the Contiki operating system and report on this implementation through trials on a Cooja simulator. The results may open new possibilities for real-world wireless sensor networks requiring reliable border routers and guide further standardization efforts in emerging technologies in support of the Internet of Things.

The proposed algorithm has a framework for sending the route request for packets by the intermediate nodes. For proposed algorithm the changes made in route discovery process just, which is as per the following:

Step 1. At the point when RREQ overwhelmed, it reaches to the nodes which are in the transmission scope of source nodes. At the point when a node gets an RREQ packet, following conditions/potential outcomes will be checked:
If it is the goal node, it sends a route reply to the sender.
Else
Step 2. If this node getting the route request for has as of late observed another route request for message from this initiator bearing a similar request identification and the target address, or if this present node's own address is as of now recorded in the route record in the route request for, this node disposes of the request.
Else:
Step 3. If {estimation of the speed of the node is more prominent than estimation of the residual battery is not as much as the limit estimation of residual battery}
Step 4. Dispose of the request.
Else
Step 5. The node includes its own address in the request packet and advances it.

Fig. 3 and 4 shows the flowchart of proposed algorithm.

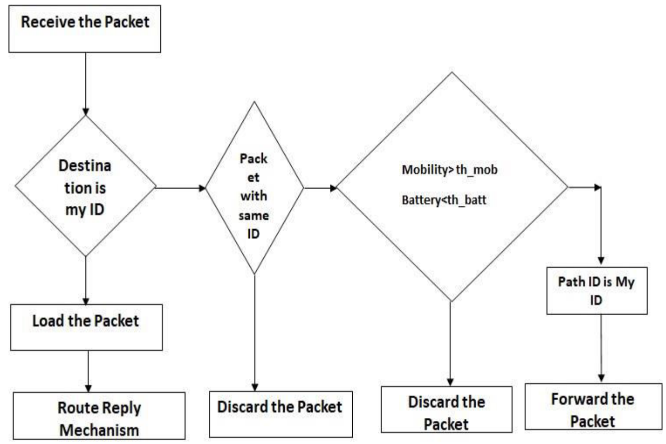

Fig. 3. Flow chart of packet delivery

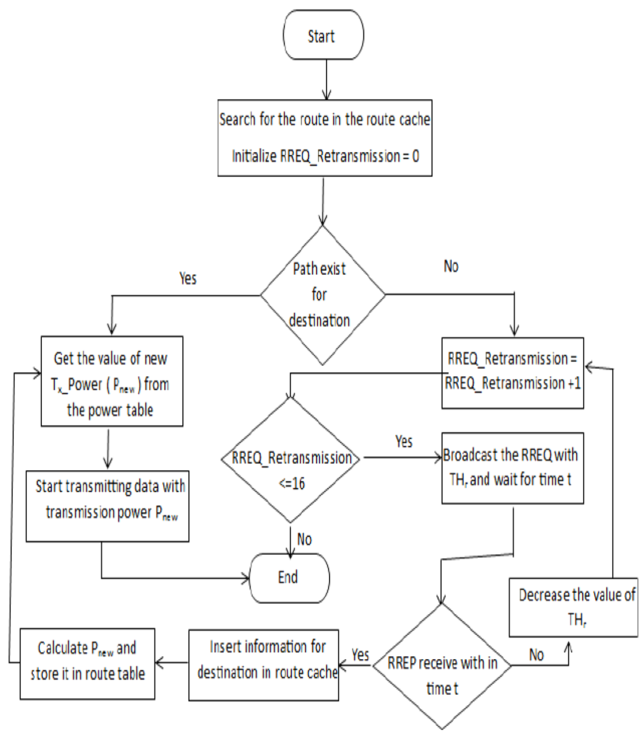

Fig. 4 (a). Flow chart of sending data in proposed algorithm

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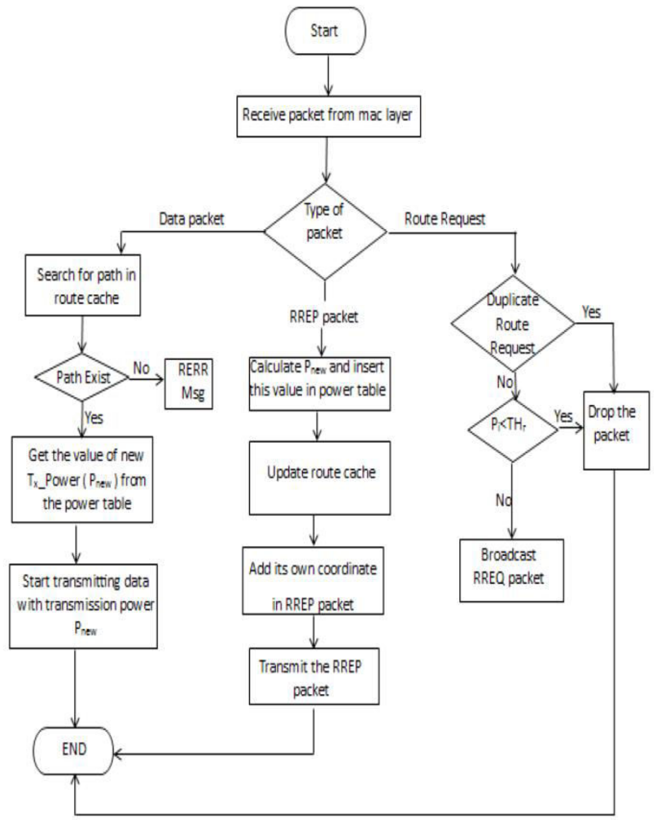

Fig. 4 (b). Flow chart of receiving data in proposed algorithm

At the point when a RREQ compasses to its destination node, destination node will reply with RREP packet. At the point when a node sends a RREP packet it adds it's organized to the RREP packet. So when the following node get this RREP it knows the area of its next node in the route to destination by this area data a node can decide the ideal transmission power required to communicate with its successor node in the route to the destination. The calculated power P_{new} is put away in a power table at every node and this is the minimum power required for effective correspondence to the following node in the route. In this figure node D replies with RREP packet alongside its coordinate so when node 3 gets the RREP from node D it know the location of node D, from this location data node 3 will compute the new power P_{new} which is the minimum power required to communicate with node D, and store this new power P_{new} in the power table. In the wake of ascertaining the new power P_{new} node 3 will forward the RREP packet alongside its coordinate. Thusly RREP will reach to node S and now node S knows the route to D alongside the minimum power required for communication. Network topology used in simulation experiments delay was expressed as the delay between the DAO packet transmission (DAO) of sending and the Acknowledgment transmission (Ack) of the receiving mote (DAG root). DAO packets were chosen because it was sent point-to-point, and not point-to-multicast, unlike DIO. Simulator captured DAO and DAO-Ack packets; we were able to get the delay using the difference of these timestamps. A packet sniffer is needed to get the packets sent into the interface. Wireshark captured the packets sent into the TUN interface using live capture, which having the PDR as simulation parameter, end-to-end latency, packet loss and throughput.

IV. Performance Analysis

The performance measures of the new proposed routing algorithm have been compared with generic Routing protocols for the calculation of throughput, packet delivery ratio, energy consumption, delay and lifetime. At start-up, all nodes are randomly deployed as the mobility model in the network. In this model, the motion parameters, such as the speed, the direction and the destination of the mobile node are selected randomly. Throughout the simulations, we consider lognormal shadowing distribution for the channel model with the specified standard deviation selected according to the measurements of routing path. IPv6 addressing and the proposed model compared with routing of RPL and other routing algorithms. The experiment is done using Contiki/Cooja simulators with implementing existing protocols using the simulator. The parameters for simulation are stated in Table 1.

TABLE 1 THE PARAMETERS USED IN THE SIMULATION

Parameters	Value	Parameters	Value
Size of target area	100 x 100 m^2	Data packet size	512 bytes
No. of sink nodes	5	Metadata packet size	25 bytes
No. of sensor nodes	95	Maximum radius, R	20m
Initial Energy	10 J	α_1	1
Transmitting	50	α_2	1

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energy	nJ/bit/m^2		
ξ_{elec}	50 nJ/bit	α_3	1
e_s	100 nJ/s	α_4	1

The network simulator helps to study the behavior of the proposed routing protocol. Using proposed routing protocol, data routing is calculated at constant bit rate (CBR) and residual energy of each mobile nodes help to find packet delivery and lifetime of nodes. The result is analyzed based on the simulator results. The parameters are set as per the values chosen for the experiments. The outcome is determined based on the simulation results.

Fig. 5 shows the performance comparison for packet delivery ratio with varying number of nodes where Fig. 6 demonstrates the performance comparison for packet delivery ratio with varying number of hops in scalable networks and Fig. 7 with the performance comparison for packet delivery ratio with varying time interval. Fig. 8 shows the lifetime of the network and Fig. 9, 10 compared the performance in terms of average Control Packet Overhead and average energy consumption. The result shows the improvement in terms of scalability, packet delivery ratio and network life-time of nodes in WSN.

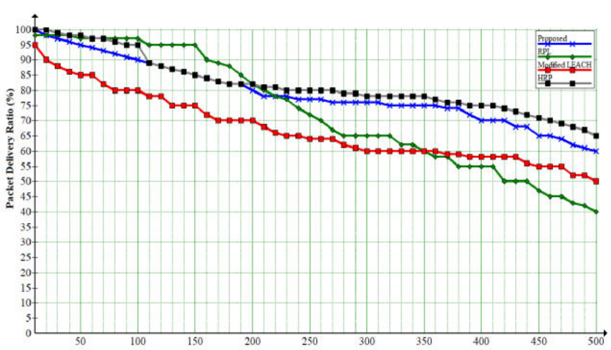

Fig. 5. Average Routing Path in Scalable Network

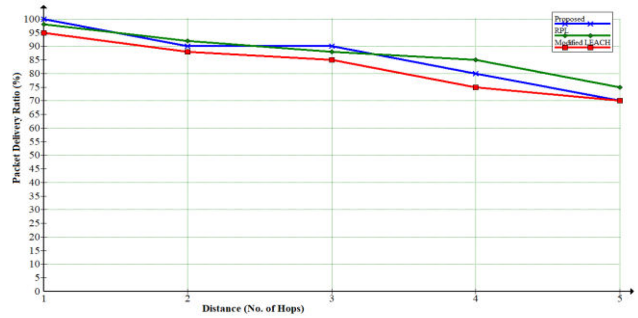

Fig. 6. Performance comparison for packet delivery ratio with varying number of hops

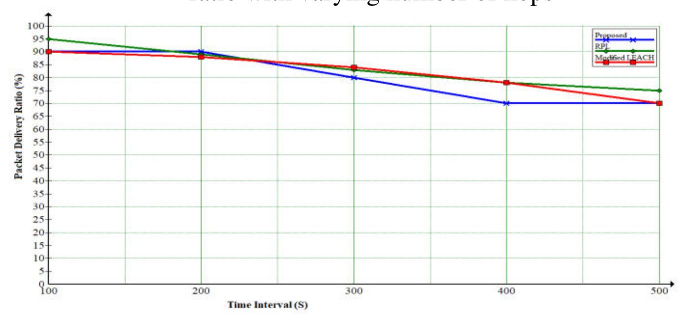

Fig. 7. Performance comparison for packet delivery ratio with varying time interval

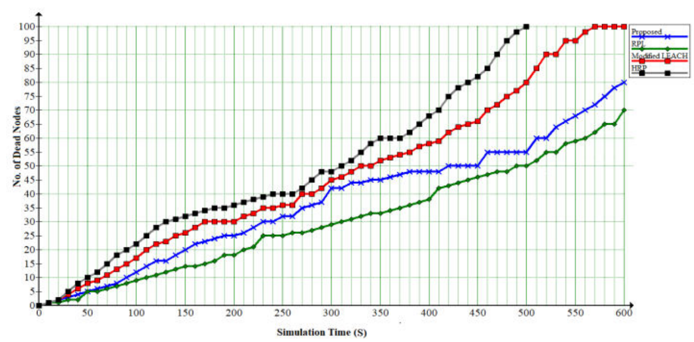

Fig. 8. Performance comparison for System Life Time

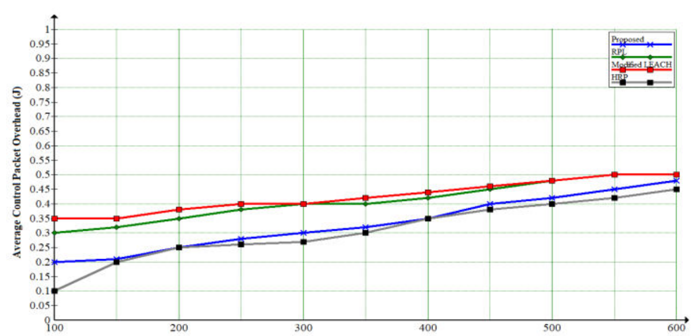

Fig. 9. Performance comparison for Average Control Packet Overhead

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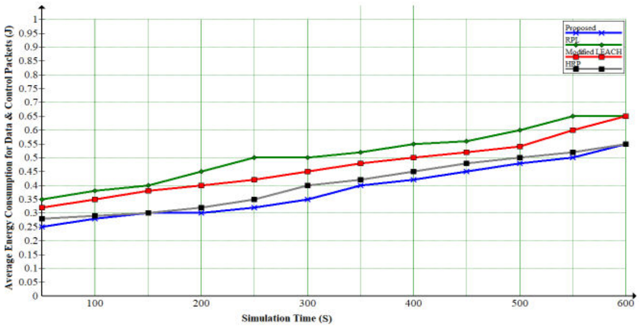

Fig. 10. Performance comparison for average energy consumption

V. Conclusion and Future Work

This study provides IETF 6TiSCH standards, which build on top of the IEEE802.15.4 TSCH MAC and PHY layer. In this paper, we have introduced Routing protocol for 6TiSCH, which is a decentralized scheduling protocol for 6TiSCH wireless networks specifically designed to address the challenges of scalable networks. It can adapt to topology changes in the network and reconfigures the schedule, which not only ensures reduced signaling overhead, but also provides high reliability in dynamic environments with efficient utilization of resources and minimizes end-to-end latency. Performance evaluation also demonstrates that the degradation in energy consumption performance is not significant when signaling overheads are also accounted for 6TiSCH protocol stack and does not require modifications at the higher layers.

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