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Energy-Aware Adaptive Trickle Timer Algorithm for RPL-based Routing in the Internet of Things

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***Abstract*— Routing protocol for low power and lossy network (RPL) is IPv6 protocol for low power and lossy networks (LLNs) devices. RPL uses the hope count and expected transmission count (ETX) as two routing objective functions (OF). Along with these two OFs, RPL uses a trickle timer algorithm to control the frequency of control messages. However, the RPL standard in its current form does not consider the node energy while routing the traffic. Due to uneven traffic distribution, some parent nodes result in energy hotspots. Similarly, the trickle timer affects the battery and overall convergence time. This paper proposes an efficient energy-aware adaptive trickle (EAAT) timer mechanism for scaling the DIO transmission based on the future energy (*FE*) and the residual energy (*RE*) information. The simulation results show that by utilizing the *FE* based OF and by scaling trickle related parameters prolongs the network lifetime and improves the routing performance.**

Keywords—RPL, DODAG, Trickle Timer, Sensor, Energy Consumption, Objective Function

I. INTRODUCTION

Internet of things (IoT) enables the communication among things or objects that are connected to the Internet. It includes many application scenarios such as smart city, home monitoring, smart factories and industrial automation [1]. Sensor node contains limited battery resource, therefore, it is necessary to provide an efficient communication mechanism to prolong the lifetime of these tiny devices. One of the ways to provide energy efficiency is to design an efficient routing protocol. The routing protocol should consider these devices special requirements such as low energy, low latency and high reliability [2] [3].

To fulfill these requirements, the routing protocol for low power and lossy network (RPL) is proposed by the international engineering task force (IETF) [4]. RPL is a distance vector (DV) routing protocol to provide IPv6 connectivity to the sensor devices having limited resources. A network is organized in RPL using the destination oriented directed acyclic graph (DODAG). It creates a parent-child-like topology using control messages called DODAG information object (DIO), DODAG information solicitation (DIS) and destination advertisement object (DAO). Using these control messages a node can join a particular DODAG [5].

One of the most important parts of the RPL protocol is to keep the routing overheads minimum to reduce the energy consumption. To achieve this goal, RPL includes an efficient trickle timer mechanism (RFC 6206) [6]. The basic idea behind the trickle timer is to control the frequency of DIO messages. Considering the battery limitations of sensor nodes; it is necessary to limit the frequency of control messages considering energy consumption and convergence time. Trickle utilizes two mechanisms to achieve this goal. First technique is to adjust the transmission period with respect to the changes in network topology. The frequency of DIO messages are varied if the network faces inconsistency (unstable) or a new node joins the network. If a node receives a consistent DIO message, it increments a counter until it reaches a certain threshold level. Then trickle doubles the transmission period until it reaches a predefined maximum value. However, if inconsistent DIO messages are detected, the transmission period is set back to a minimum value. Second method is the suppression of control packets transmission in case of same information is transmitted by enough number of neighbors.

The key element in RPL is to select the parent node by considering both the energy and load balancing simultaneously. In addition to that, adjusting a control packets transmission with respect to the current energy status of the node is highly beneficial in scarce resources network. In this paper, we provide an effective method to offer an energy-aware adaptive trickle (EAAT) mechanism to reduce the node failure probability and improve the average lifetime in a wireless network environment. For adaptive scaling the DIO transmission in trickle timer, the redundancy constant value k is adjusted according to node future energy (*FE*) consumption condition. The trickle timer affects the battery and overall convergence time. Therefore, if the *FE* is predicted more and DIO information is consistent, the parameter k is decreased to allow longer DIO interval, which in turn reduces the control traffic energy consumption. This method can efficiently jointly reflect the parent's node energy condition, better load distribution, and improved network lifetime.

The used notations in this paper are provided in Table I. The rest of the paper is organized as follows. Section II discusses the background and related work proposed for RPL protocol. Section III provides the system model, whereas, section IV explains the proposed protocol. Section V demonstrates the simulation results and the last section VI concludes the paper.

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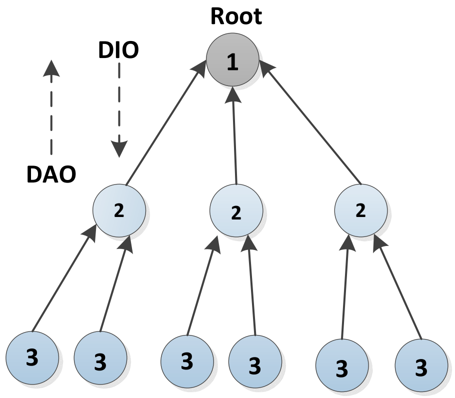

Fig 1. RPL DODAG illustration

II. BACKGROUND AND RELATED WORK

A. RPL

RPL is a de-facto routing standard for LLN and is standardized by IETF. It uses a distance-vector based routing due to the LLN devices energy limitations. The protocol utilizes IEEE 802.15.4 MAC and physical layer. The route is established by building a directed acyclic graph (DAG). In RPL, the network is organized using DODAG. In each DODAG, the nodes are ranked based on the specific objective function (OF) [5].

During the configuration phases, the sink node broadcast the DIO message to all the nodes in its vicinity. The receiving nodes save the sink node in their routing table for future communication. Next, in the route establishment phase, the nodes compute their ranks based on the received DIO message. Based on the rank information, the nodes select the preferred parent node. During the communication phase, the nodes transmit the data packets to the sink node via their preferred parent. In case of changes in the routing topology, a DAO message is sent to update the routing table.

RPL defines two OFs for path selection and routing decision. These OFs are objective function zero (OF0) and the expected transmission count (ETX) for parent selection [7] [8]. OF0 find the nearest path to the root node irrespective of the link condition. Similarly, the ETX metric based OF ranks the nodes on the basis of their link qualities towards the root node without considering other important metrics such as node energy, workload, and transmission power. The node is given a rank 1 if it's a root node and so on. Selecting a path based on only the distance from root node may cause packet loss and delay in a large-scale network because it may choose energy exhausted nodes or a congested path. Especially nodes closer to the root node faces high rely burden and thus their battery depletes faster as compared to the other nodes [9]. The RPL network topology is illustrating in Fig. 1.

B. Trickle Timer Algorithm

The trickle timer is a scheduling technique with broad applications including control traffic scheduling and service discovery. IETF standardized the trickle algorithm and later adopted by the RPL protocol to manage the frequency of control messages. Trickle control the flow of messages either by suppressing the transmission or by dynamically adapting the transmission period if the network is consistent or inconsistent.

Table I. Key Notations

Symbol	Description
p_n	List of parent nodes
v_n	List of child nodes
s	Sink node
c	Message counter
l	Trickle interval length
k	Redundancy constant
l_{min}	Minimum length of current transmission
l_{max}	Maximum length of current transmission
FE	Future energy
WL	Node workload
RE	Node residual energy
ETX	Expected transmission count
$e(d)$	Energy required to transmit packet at distance *d*

The trickle algorithm works on each node as follow:

It consists of three variables;

- A message counter *c*.
- Trickle interval length *l*.
- A random interval length *t*.

Trickle also contains three configuration parameters;

- A redundancy constant *k* (a value specified by the user and greater than zero)
- Minimum length of current transmission I_{min}
- Maximum length of current transmission I_{max}

In the start, trickle set the counter *c* to 0 and interval length *I* to any value in the range between $[I_{min}, I_{min}$ x $2^{I_{max}}]$ and picks the transmission period *t* at random from $[I/2; I]$. Whenever a node hears a consistent transmission, which means there is no change in the routing metrics (e.g., congestion status, link quality, or hop count), trickle increments the consistency counter *c* by 1. Trickle transmits if and only if *c* is less than *k* ($c<k$). Otherwise, the transmission is suppressed. When minimum interval length expires, trickle doubles the interval length. If trickle hears an inconsistent transmission, which means there is a change in the routing metric, it resets the trickle timer to initial value.

C. Related Work

Several studies are presented to study the performance of the RPL protocol such as queue utilization based RPL (QU-RPL) is proposed to evaluate the end-to-end delivery performance [10]. To adjust the trickle timer, a queue loss is representing the inconsistent transmission. Therefore, the value of trickle timer is set to an initial value when a queue loss occurs continuously. QU-RPL balances the routing tree using the hop counts and queue utilization of neighbor nodes. However, the energy consumption of the nodes is not considered which may lead to the selection of low energy node and thus a link failure may occur. Similarly, another mechanism combines the RPL protocol with backpressure routing which leads to better throughput performance [11].

Algorithm 1: Adaptive Trickle Timer (EAAT) Algorithm

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Input: $(p_1, p_2, p_3, \ldots., p_n), (v_1, v_2, v_3, \ldots., v_n) \in N$
Begin:
1.  Form RPL DODAG using algorithm proposed in [7].
A. Objective Function:
2.  At any time slot $t \in T$, do
3.  Compute $FE$ based OF using equation (1)
B. Trickle Timer:
4.  Initialize the trickle timer
5.  $I = I_{min}$
6.  Counter $c = 0$
7.  while $RE >= RE^{th}$, do
8.     Transmit DIO at time interval $t$ between $[I/2; I]$.
9.     if consistent transmission,
10.        $c = c + 1$
11.        if $c <= k$
12.           Transmit DIO
13.        end if
14.    else
15.        Suppress DIO transmission
16. end if
17. end while
18. while $RE <= RE^{th}$, do
19.     Compute the redundancy $k$ value using equation (2)
20.     Initialize the trickle timer
21.     $I = I_{min}$
22.     Counter $c = 0$
23.    Set new $k$ according to equation (2)
24.    Repeat steps 8-16
25.    Update DODAG
26. end while
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We believe that the IoT nodes routing must be aware of the energy consumption at each node. The energy efficient and path reliability aware objective function (ERAOF) utilizes a composition of routing metrics to provide a reliable energy efficient path [12]. To achieve the load-balancing, a node workload must be taken into consideration along with the energy metric for a longer lifetime.

The scalable context-aware objective function (SCAOF) is based on a weighted sum of three metrics, i.e., node connectivity degree, node energy level, and node position in the routing tree relative to the parent node [13]. The objective of this method is to find a delivery probability for each sensor node. The fuzzy logic based OF (OF-FL) is proposed which combines the set of metrics including point-to-point delay, ETX, hop count, and energy level to provide an optimal parent selection decision [14]. Similarly, Brachman et al. studied the network topology using OF0 and link quality OF (LLQ OF) [15].

The energy costs of transient node failures in an RPL network is examined in [16]. This mechanism shows the cost of node failure and how it impacts energy efficiency of the entire network. To estimate the lifetime of the bottleneck nodes, a routing metric expected lifetime (ELT) is proposed which consider the amount of traffic and link reliability to estimate the energy hotspots [17]. However, this mechanism does not consider adjusting the tickle timer.

Similarly, various schemes are proposed to particularly enhance the performance of the trickle algorithm. Trickle-F prioritizes each node depending on how many numbers of times it has been suppressed from transmitting [18]. Trickle-F gives priority to nodes in the next round for transmission, if it has spent a long time without transmitting. The short listen period of trickle produces latency. To reduce the latency, an optimized trickle named opt-Trickle is proposed [19]. According to opt-Trickle when a trickle hears an inconsistent transmission, choose a next transmission period from [0: *Imin*] to resolve inconsistencies faster. Similarly, the dynamic trickle algorithm makes the listen-only period chosen dynamically which depends on the number of neighboring nodes. Trickle-Plus introduced three new configuration parameters to handle the convergence time and power consumption issue [20].

In the current study, we analyze the RPL by adjusting the trickle timer using the *FE* consumption of the IoT node. To provide the LLN requirements, we design a communication routing topology model on the basis of the node workload, its residual energy (*RE*), link quality (ETX) and distance information. The redundancy constant k in the trickle algorithm is adjusted according to the final OF. The main contributions include a load balancing topology model based on the composition of different routing metrics. In this model, nodes are given a rank based on the *FE* consumption. The candidate parent node from the list of parent nodes set is selected based on the combination of its buffer occupancy i.e., workload, its link quality, *RE* and distance information

III. SYSTEM MODEL

The network is formed based on parent-child topology for data transmission forming a routing graph called DODAG. There is *N* number of nodes in the network which are ranked from 1 to *m.* These nodes are further divided into a set of parent nodes $(p_1, p_2, p_3, \ldots., p_n)$ and child nodes$(v_1, v_2, v_3, \ldots., v_n)$. The candidate parent node is given a rank 1 if it is a root or sink node *s*, i.e., $if\ p_i \in s, \forall\ p, v, s \in N$.

Each node collects the buffer occupancy information at each time slot *t.* The control message (DIO) flows in the downward direction from parent to the child node, which contains information about the OF. The routing metric *FE* is obtained from OF. The OF is based on the candidate parent node workload, which is a buffer occupancy, link quality, i.e., ETX, and distance information which in turn represent the energy required to transmit a single packet $e(d)$.

We assume that all nodes *N* utilize IEEE 802.15.4 wireless links for communication. The root node uses IPv6 for communication with servers. The ETX metric is used to approximate the link quality during each time interval. The ETX is calculated by taking the inverse of the probability of successful packet delivery.

IV. PROPOSED ENERGY-AWARE ADAPTIVE TRICKLE TIMER ALGORITHM

A. Routing Metric

Energy consumption based RPL OF play a pivotal role in the lifetime of the sensor network. The capability of switching parent node based on both the link condition and node condition results in reducing congestion and delay in the network. The workload of node p_i includes the self-load and the load due to the sub-tree (children nodes) which can be acquired by observing the buffer occupancy at specific time duration *t*. Similarly, we assume that initial energy of the node is known beforehand. Each node $n \in N$ generates packets at a predefined rate. The parent node p_i *RE* at time slot *t* is obtained by computing the total energy spent during packets transmission, packets reception and idle state.

According to the first order radio model [21], the energy to transmit a packet is a function of distance along with the size of the packet. It depends on the following factors; (i) the energy requires to run a transmitter or circuitry, (ii) transmit amplifier energy to achieve acceptable energy over noise ratio and (iii) the path loss index. ETX provides reliable link quality estimation, therefore the link is given a priority based on the distance of the node to the destination because the probability of successful transmission decreases with the increase of distance.

To provide a better energy aware OF to improve the performance of RPL, this paper uses a *FE* consumption based OF. The proposed OF chooses the path with low probability of link failure. As a result it distributes the load accordingly. Thus, we aim to minimize the energy consumption of most constrained parent node.

$$FE = ETX.WL.e(d) \quad (1)$$

where WL is workload of candidate parent node and $e(d)$ is the energy required to transmit a single packet at a distance *d*. The node ranks are set and embed in the DIO message along with their *RE* values.

B. Adaptive Trickle Algorithm

As explained in section II-B, the standard trickle timer algorithm configuration parameter *k* helps in adjusting the transmission interval. The value of *k* is constant in the standard definition.

In the standard RPL RFC document [4], the typical value of *k* is 10 for suppression mechanism. The value of *k* is dependent on network topology and application scenario. Assuming a random network topology and energy-aware application scenario, it is highly desirable to set the *k* optimally for each node. The small value of *k* means, the trickle algorithm increases the interval length with few consistent messages and vice versa. The network lifetime is one of the main considerations while deploying a sensor network. The nodes closer to the sink node usually carry high rely burden. Using a proposed routing metric along with dynamically adjusting the trickle redundancy constant *k* can efficiently improve the energy consumption.

The variation in *k* can affect the number of DIO messages transmission. When *k* value is set larger, a node transmits more number of DIO messages and the convergences time decreases and if the *k* value is small, the node transmits fewer DIO message. We bound the *k* value with respect to the energy information of the node. Consequently, the value of *k* increases or decreases depending on the *FE* and current *RE* value of the critical nodes. In this way, we can prolong the average lifetime. The critical nodes are the ones which have a power level below a certain threshold point.

The parent node measures its *FE* value and current *RE*. The value of *k* is calculated by subtracting the percentage value of *FE* from the percentage value of *RE* as shown below.

$$k = [RE\,\% - FE\,\%]/2 \quad (2)$$

Algorithm 1 illustrates the proposed *FE and RE* based adaptive trickle mechanism for RPL routing protocol. The detail description of the proposed protocol is explained as follows: the candidate parent nodes ($p_1, p_2, p_3, \dots, p_n$) initializes to calculate the number of routing metrics for the current intervals *t*. Firstly, a node measures the link quality using ETX metric. This metric predicts the paths where the fewest expected number of transmissions is required which in turn reflect the node energy consumption in transmission phase. Thereafter, a workload is calculated which reflects the buffer occupancy. The nodes calculate their *RE* by calculating the energy spent during packets reception, transmission, and processing as well as idle state energy. Similarly, it also observes energy require to transmit a single packet. Subsequently each node gets rank using the proposed OF calculation. These rank information in the form of *FE* along with the measured *RE* values are embedded in the DIO message to update the child node.

The child node receives routing metric information, encapsulated in the DIO message. In parallel, each node adjusts the trickle setting according to the measured *FE* and *RE* values. After the redundancy period is dynamically chosen based on the threshold energy level, the node checks the consistent or inconsistent state during listen the only period. If a node hears a message with a new ID and all neighbors exchange the same message, it remains in a consistent state. Afterwards the node transmit if the counter *c* < *k*. However, the transmission is suppressed if the counter c is more than or equal to the *k* value. We argue that in case of energy scarce network, the OF must consider the energy factor along with the other link and node level decision parameters. Similarly, the trickle parameter should be adjusted with respect to the node energy information. The proposed EAAT protocol handles the scenario for energy hotspot nodes by balancing the control traffic overheads and energy consumption collectively.

Selecting a preferred parent node by using only the queue utilization or only the energy consumption or link quality may result in poor parent choice. Hence, it ultimately leads to node failure or to the selection of an already energy exhausted node. We proposed that a node must consider a link level and node level metrics jointly. Parent node selection based on its *FE* would lead to maximizing the lifetime of the network. In other words, we prefer the energy balancing along with load-balancing.

V. PERFORMANCE EVALUATION

In this section, we provide simulation-based results to illustrate the performance of the proposed EAAT and the original RPL protocol. In the simulation, we set the region size to 500 m $*$ 500 m with 30 nodes. Each node has a buffer size of 50 packets and packets size of 127 bytes. We assume

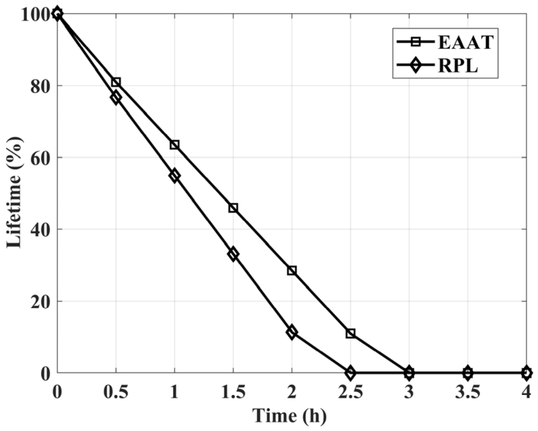

Fig 2. Network lifetime during total simulation time.

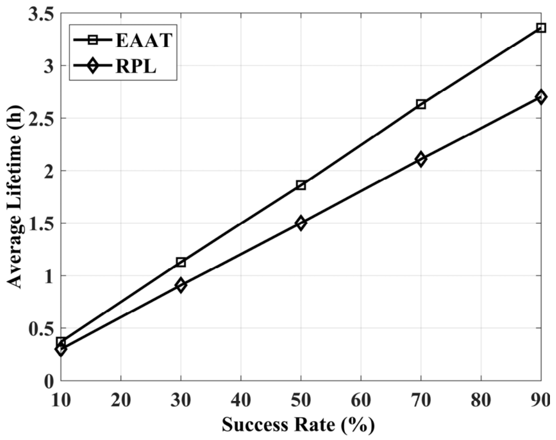

Fig 3. Average lifetime with to varying success rate.

that all nodes have the same battery size and initial energy. Table II provides the summary of parameters used in the simulation.

The nodes closer to the sink node deplete their energy faster than other nodes. The average lifetime refers to the time until the first node power completely drains in the network. In EAAT protocol, the redundancy counter c is zero at the end of current interval or at the beginning of the new interval. Each node adjusts the redundancy constant *k* with respect to their energy level. This leads to a more average lifetime of the node as it decreases the number of the DIO messages transmission.

We observed the network lifetime as shown in Fig 2. The lifetime shows the energy balancing scenario of the network due to the balanced load and optimized trickle mechanism. Fig. 2 shows that the average lifetime of a network using EAAT protocol is significantly more than the original RPL protocol utilizing conventional trickle mechanism.

Similarly, we also observe the lifetime pattern of original RPL and our proposed EAAT algorithm with respect to the varying link success rate as shown in Fig. 3. We explore the effect of link quality parameters as the link quality effect the topology and consequently the lifetime of the network. The link quality is an important parameter because the node requires more retransmissions to deliver a packet to the destination. When the link success rate increases, the proposed EAAT based RPL protocol shows the longevity of the network lifetime.

Table II: Simulation Parameters

Parameter	**Value**
Number of nodes	30
Network size	500 m x 500 m
Simulation duration	14400 seconds
Buffer size	50 packets
Packet size	127 bytes
I_{min}	2
I_{max}	16
Redundancy factor *k* for RPL	10
Reception success rate	10, 30, 50, 70, 90
RPL objective function	MRHOF
Network topology	Random

VI. CONCLUSION

The load and energy balancing is a crucial factor that affects the energy consumption of the sensor node. The load and energy balancing can be achieved by utilizing the energy-aware objective function along with the efficient trickle timer. The trickle algorithm affects the frequency of control packets. In this paper, we studied a modified trickle mechanism for RPL protocol. For the proposed mechanism, we utilized our future energy based objective function to select the routing path. We studied the proposed energy-aware adaptive trickle mechanism which adjusts the trickle related parameter called redundancy factor *k* according to the node energy condition. Simulation results show the network lifetime is significantly enhanced by using the proposed mechanism. In the future, we plan to study the effect of different redundancy factor *k* value during network initialization phase along with different network densities.

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