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WRF-RPL: Weighted Random Forward RPL for High Traffic And Energy Demanding Scenarios

PEDRO DAVID ACEVEDO[1], DALADIER JABBA[1], PAUL SANMARTÍN[2], SEBASTIÁN VALLE[1], AND ELÍAS D. NINO-RUIZ[1]
[1]System and Computer Engineering Department, Universidad del Norte, Barranquilla 080001, Colombia
[2]System and Computer Engineering Department, Universidad Simón Bolívar, Barranquilla 080001, Colombia

Corresponding author: Pedro David Acevedo (pdacevedo@uninorte.edu.co)

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ABSTRACT The wireless sensor networks (WSN) are immersed in multiple areas of knowledge and are the alternative that allows analyzing, solving, and preventing problems under different facets. The RPL protocol (IPv6 Routing Protocol for Low power a Lossy Networks) arises for the management of this type of network restricted by their physical capabilities through different rules and operations that simplify the communications and constructions of the WSN. Although RPL is an efficient and standardized protocol, it does not consider high traffic handling and presents severe problems regarding load balancing, which leads to service disruption. In this article, WRF-RPL is proposed as a protocol for considering load balancing over RPL to distribute communications and messages into a network topology to avoid one preferred parent's congestions. The proposed protocol aims to improve the network's lifetime and the packet delivery through source nodes to the sink in an energy-efficient manner. Different simulated scenarios were conducted over the Cooja simulator. The results show that WRF-RPL protocols outperform the standard RPL protocol over Network Lifetime, PDR, control message overhead, and energy consumption compared with other existing protocols.

INDEX TERMS Wireless sensor networks, routing protocols, energy efficiency, RPL, load balancing, objective functions.

I. INTRODUCTION

In recent years, we have seen the immersion and impact of the Internet of Things (IoT) paradigm in different areas of knowledge. IoT allows the connection of multiple devices of different characteristics under the same network with a common goal [1]. These devices can range from a sensor that detects movement to report intruders in a company's facilities to a household appliance with integrated circuits and connections that can be configured or programmed remotely. Smart cities [2], transportation [3], healthcare [4], [5], public services [6], and monitoring [7] are some of the areas in which the use of IoT is essential for the solution of different problems. These solutions are possible because the IoT paradigm application allows the collection, composition, and analysis of critical data generated in these existing scenarios.

Wireless sensor network (WSN) is one of the categories that make up the IoT paradigm, which describes multiple sensors distributed over an area or zone of interest for data collection purposes. Such sensors have many constraints, from low power capacity to unstable connections in the environment. Consequently, how the information is collected and relayed, taking into account the devices' hardware limitations, will determine the efficiency of the proposed architecture. As a result, the IEFT (Internet Engineering Task Force) established a standard for routing packets within WSNs called RPL (IPv6 Routing Protocol for Low power a Lossy Networks). RPL constructs a destination-oriented directed acyclic directed graph (DODAG) for the most efficient connection and communication between nodes, based on the distance between nodes and their range. Additionally, the RPL protocol facilitates data relaying by having mechanisms for construction, route maintenance, and cycle avoidance [8].

One of the significant problems of any network architecture is to operate with high packet traffic, which increases the possibility of congestion and delays in communications. This congestion eventually reduces network performance and directly impacts Quality of Service (QoS) aspects

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such as latency, energy consumption, reliability, and packet delivery [9]. Therefore, a load-balancing scheme is required to overcome the high rate present in this type of congested scenario. WSNs are not exempt from this problem, but despite this, the IEFT does not define a load balancing scheme for the standard RPL protocol. Therefore, delineating an efficient load balancing scheme associated with RPL has become an area of interest for the scientific community.

Multiple types of research have emerged to propose a load balancing scheme for RPL, according to the quality of service (QoS) standards [1] and the physical limitations of WSNs. Data-demanding scenarios are a possibility when operating this kind of WSN network. Burst traffic is a common feature of this type of topology. This type of traffic is defined as peaks in the number of messages/packets transmitted on the network, causing the nodes to be prone to congestion and poor load distribution. Therefore, it is recognized that data traffic can be highly dynamic since there will be moments where events may occur that require flooding the network. Critical events can be in environmental monitoring (disaster prediction/detection, sporting events), applications of Smart Cities, and industrial networks, among others. This article proposes the WRF-RPL routing protocol oriented to high traffic and energy-demanding scenarios. This protocol, through the combination of two network metrics (remaining energy, parent node count) and the consideration of multiple communication paths, contemplates the possibility of distributing the load present in the sensor network.

The rest of the article is divided as follows: Section 2 presents the different scheme proposals presented in the literature; Section 3 describes the generalities that define the RPL protocol (its operation, components, and target problem); Section 4 summarizes the contributions of the article regarding the protocol proposal presented; Section 5 delimits the design of the balancing proposal, addressing the theoretical, algorithmic and operational aspects of this new scheme; Section 6 presents the results obtained when evaluating the efficiency of the proposed protocol against the standard RPL protocol; and finally, Section 7 presents the conclusions and future work.

II. RELATED WORKS

The RPL protocol delimits as an external component the construction and design of the objective function. The flexibility in updating the objective function makes it possible to adapt how routing information operates to the needs of the topology. Multiple strategies have been defined for the appropriate OF for RPL operability, including proposals such as those described in [10]. The objective function in [10] seeks to minimize a network evaluation metric for choosing the range between nodes and selecting the parent node. This metric can correspond to the value given by ETX or any additive metric; its value increases as a path and is traced in the network.

Similarly, another objective function defined as a basis on RPL is the so-called OF0 [11]. Authors use the range mechanism defined on RPL or the number of hops to that node as an evaluation metric. When considering this metric, it seeks to define the number of retransmissions per packet to choose the closest communication routes to the sink node.

The MRHOF and OF0 function have problems in high traffic scenarios due to the congestion of the relay nodes, which leads to reduce the network lifetime. An alternative objective function oriented to load balancing is described in [12] where a routing protocol called LB-RPL is proposed. LB-RPL considers the workload of the network, defining a counter to activate a delay in sending DIO packets so as not to report with reduced availability and thus allow the node to relieve the traffic it is processing. It also establishes actions for using multiple routes over RPL by considering more than one node to choose the next hop through a random exchange to not overload the same node with delayed tasks.

Another protocol oriented to load balancing is defined in [13]. The authors present the objective function called LB-OF, which uses the count of child nodes as a next-hop evaluation metric. This procedure is performed by sending control messages to update the so-called "Child set", which stores the child nodes that the node has. This child count metric seeks that the choice of the parent node is oriented to nodes that use parents with a smaller number of children to avoid choosing overloaded parent nodes as the next hop. The combination of multiple metrics is one of the most widespread approaches among balancing proposals [14]. In [15], authors define a model for load balancing called ALABAMO, in which, based on the MRHOF objective function, they determine the appropriate selection of the parent node by analyzing the number of packets that have been sent by that node (workflow) after the ETX value exceeds a preset limit.

Similarly, the scheme proposed in [16], adds the candidate parent count (PC) metric and ETX to select the parent node thinking about high traffic scenarios, which involve a high packet forwarding rate. Therefore, it considers allowing to have the possibility of choosing different candidate parents for the distribution. In [17], the "Child count" metric is employed by sharing such information through DIO messages. However, since the sending of the DIO message may vary between different time intervals, the authors propose a modification to the Trickle timer mechanism, in charge of the periodicity of DIO sending, by adding the so-called FastPropagationTimer. This timer is activated when a parent node undergoes modifications to the number of connected children, thus frequently informing the node's current state.

Similarly, the use of the multipath feature over RPL is defined in several OF designs, such as the one proposed in [18], where the Duty Cycle mechanism (hibernation mode until a packet is received) is used globally. The balancing feature consists of nodes performing anycast communications to generate opportunistic routes in the absence of a preferred path. The balancing obtained in this OF occurs when a congested node starts to ignore incoming packets from its neighbors to avoid possible overloads. The obtained balance allows retransmission tasks to be addressed by neighboring nodes that have processing availability, thus avoiding data loss. This approach may result in more significant flooding of packets throughout the network, as communications are anycast at all times.

The objective function is described in the buffer utilization considerations in [19], where the Context-Aware Routing Metric (CARF) is introduced for the parent selection decisions. Such metric considers the buffer utilization and the remaining energy of the candidate node in an additive way (considering the connection chain). Similarly, the authors propose a mechanism to avoid the Thundering herd problem, which consists of gradually increasing the RANK of the nodes to prevent new connections from being attracted to a single node. Other approaches to determining the best load distribution strategy are described in [20], where an objective function based on the Power-Delay Product (PDP) metric is proposed [21], which takes into account both the energy consumption and the delay at the time of packet transmission. OF establishes the metric when the parent node change, implying that some situation has occurred, and defines a modification of the DIO message to transmit the information regarding the energy of the path, the delay, and the message reception time. In [22], the NG-RPL objective function is described, which seeks to improve the P2P communications of the RPL protocol. This proposal builds and manages the topology by determining the communications network according to the best possible routes. According to the information collected through DAO, DAO-ACK messages, and the piggybacking mechanism, these routes are selected and established from the sink node.

Other types of proposals are described in [23], where the objective function lbRPL is described. In this proposal, the metric called Load Balancing Index (LBI) is considered, which considers the composition of the energy consumption metrics, ETX, and the count of parents or nodes of a communications path. This protocol describes how to improve network lifetime and network stability. Another proposal aimed at energy consumption is presented in [24], which defines the objective function EC-OF. This function considers more than one metric for selecting the next hop or preferred parent: ETX, Hop Count, and energy consumption. These metrics are added through Fuzzy logic in which, from some input parameters and their characteristics, it generates an output that determines the parent's selection criteria. This modification allows the authors' proposal to improve the RPL protocol in balancing the energy of all the nodes of the network. In [25], RPL-FL is described how the protocol modifies the operation of the Trickle algorithm mechanism. This proposal considers the non-random definition of the time intervals for sending messages and avoids overhead by defining I_{min} intervals with a significant value from the beginning, that is, when the RPL tree is built. RPL-FL provides the best values in overhead, packet delivery ratio (PDR), and energy consumption.

Accordingly, this paper proposes the WRF-RPL protocol of an alternative to RPL in high traffic scenarios where a load balancing scheme is required. This protocol allows extending the network's life through the efficient use of energy and manages to reduce the loss of network packets, especially in WSN scenarios with high data traffic, where congestion and packet drops are more frequent than in other types of scenarios.

III. RPL OVERVIEW

In wireless sensor networks (WSN), where limited hardware and processing resources are available, it is necessary to have a routing protocol that allows efficient communication between nodes. Therefore, the IEFT, through the ROLL (Routing Over Low power and Lossy networks) work team, defined the standard protocol for this type of communications called RPL (IPv6 Routing Protocol for Low power a Lossy Networks) [26]. RPL meets all the requirements to support a sensor network's communications under this type of restricted scenario.

RPL is defined as a proactive routing protocol, forming a topology based on the nodes' distance from the respective sink node. In this way, using the distance vector procedure, the construction of a DODAG (Destination Oriented Directed acyclic graph) or a tree that delimits the nodes' connections within the network is established. The purpose of this is to allow multi-hop communications through the closest devices.

The RPL protocol has different ways of establishing connections, such as point-to-point (P2P), point-to-multipoint (P2MP), and multipoint-to-multipoint (MP2P) communications. For the construction of the topology, there are three types of nodes:

1) Source nodes. Nodes that are in charge of collecting the information, usually through the use of integrated sensors.
2) Leaf nodes. They are also sensor nodes, but they do not perform relaying tasks. and,
3) Sink nodes or border routes. Unlike the others, nodes have more significant processing and energy capacities to compile all the network information.

Nodes communicate via ICMPv6 messages or control messages to initiate and maintain connections and network topology formation. Additionally, to accomplish communication tasks, nodes employ the objective function (OF) mechanism to handle routing decisions within the network.

A. CONTROL MESSAGES

Control messages in RPL are a predefined ICMPv6 packet with (i) a header composed of 3 fields: Type, Code, and Checksum, and (ii) a message body that includes contents and some options [27]. RPL specifies the type of ICMPv6 message using code 155 and manages the format of each control packet. Four control messages are defined [28]:

1) DODAG Information Solicitation (DIS): it is used to request sending the DODAGs Information Object (DIO) to the neighbors in the network.

2) DODAGs Information Object (DIO): contains pertinent information regarding current $RPL_{I}nstanceID$, configuration parameters, candidate parent information, DODAG maintenance, among others.
3) Destination Advertisement Object (DAO): transmits information to register each node visited on a downward route (or English downward route).
4) Destination Advertisement Object (DAO-ACK)): informs the node that sent the DAO message that the message was received.

B. DODAG CONSTRUCTION

Figure 1 describes how the RPL protocol operates. First, the node BR (Border Route) sends the DIO (DODAGs Information Object) message with information of the current node, such as the value of *RP_Instance*, *DODAG_ID*, *OCP* (Objective Code Point), and *RANK* to its close neighbors. This message is received by *NA* (Node A), who establishes BR as its parent node. Then NA calculates the rank (*RANK*) based on the defined objective function (OF) and responds with information about the chosen route to the sink node in a DAO (Destination Advertisement Object) message to BR. The range obtained will allow *NA* to establish how far it is from the Sink node in terms of the number of hops. Parallel to the process generated by *NA*, *NC* (Node *C*) asks for information about the architecture through the DIS (DODAG Information Solicitation) message to be part of the WSN network. Subsequently, the same procedure done by the *BR-NA* is performed by the neighbors ($NA - NB$, $NB - NC$), assuming no more sink nodes within the scheme. At the end of sending the DIO message, a downstream communication will be established to inform the DODAG scheme to the sink node, such as the route connecting the nodes.

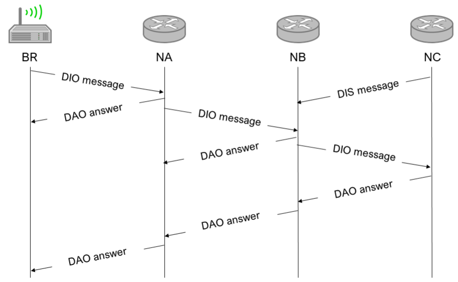

FIGURE 1. Timeline of control message in RPL [29].

C. OBJECTIVE FUNCTIONS

RPL employs an objective function (OF) to determine parent node selection and transmission decisions. Therefore, an OF defines (i) how to compute the link cost, (ii) how to select the parent node (when, who, and how many), (iii) how to compute the rank value, and (iv) how to advertise the path cost [30]. The design of an efficient OF remains an open research problem. Based on the vast number of RPL applications, these objective functions can be defined according to existing needs. However, the ROLL task force proposes two default OFs along with RPL, and these are MRHOF (Minimum Rank with Hysteresis Objective Function) [10] and OF0 (Objective Function Zero) [11].

D. LOAD BALANCING OVER RPL

The RPL protocol does not consider load balancing since it is oriented to handling low data traffic [3]. Therefore, there are deficiencies when situations arise that require load distribution or when facing a scenario with a high data flow. These deficiencies lead to an exponential increase in data loss caused by buffer overloads at the nodes and an increase in the energy consumption of the affected nodes [17]. These congestions underlying the load maldistribution cause subnets' formation not connected to the sink because the blocked nodes (bottlenecks) considerably reduce the success rate of packet retransmission. Congestions result in service disruption and poor performance of the WSN topology.

Besides, based on the ETX metric, which considers only the quality of communications between two nodes, it is impossible to guarantee performance in a high traffic scenario since a limited view of the general behavior of the network is being established. Despite the existence of the parent mechanism, which operates when there is a decrease/improvement in the metric assigned to the node, it may not be effectively employed when considering limited information (ETX) of the current state of adjacent nodes. A different scenario may arise when considering metric(s) topology characteristics related to data congestion (buffer usage, node energy, among others).

Other situations in which the RPL protocol is subjected to load balancing problems are described in [14]. One of these problems is called the Thundering Herd problem. This problem occurs when a new node connects to the DODAG with a lower rank than the nodes already in the topology, and a parent change is needed. Therefore, all of them will take that node as the next hop, which implies immediate congestion (Figure 2).

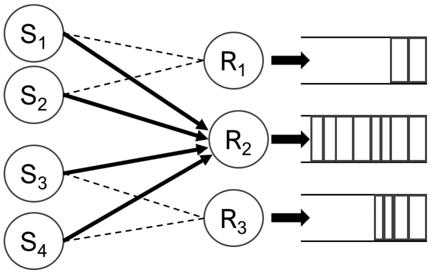

FIGURE 2. Buffer utilization. Nodes S1-S4 represent source nodes, nodes R1-R3, represent parents, in this case R2 is chosen as the next hop by most nodes, which causes congestion in its buffer.

The Hot spot problem is also described, in which a node uses all its resources when it has to handle a high demand of tasks (census or retransmission). The problem leads to the exhaustion and disappearance of the node in the network topology. Another problem is the bottlenecks, referring to nodes that are one hop away from the sink. These nodes are a weak point in the topology because, in addition to handling their data sending, they also deal with the traffic generated in the network (an increase of the delay tasks) since they are the access bridge to the sink. All these situations lead to an increase in the loss of packets sent in the network, implying difficulty in fulfilling the initial objective of the WSN [31].

IV. CONTRIBUTIONS

This paper aims to define a routing protocol proposal based on RPL for handling high traffic and load balancing under WSN scenarios with a single gateway. This proposal seeks to extend the network lifetime and increase the percentage of successfully received packets to achieve the census objective. In scenarios where the data rate is demanding [32], [33], the proposed protocol operates effectively by presenting modifications in the construction and maintenance of the DODAG using a composite routing metric (considers more than one metric). Cooja simulator is employed for protocol validation in different network scenarios for comparisons against the standard RPL protocol. The contributions can be summarized as follows:

1) A new objective function is proposed that modifies the operability of the RPL protocol, called Weighted Random Forward RPL (WRF-RPL). This protocol has the following attributes:
    1.1. According to the score obtained in the evaluation metric of the parent node by OF, communications and selection of the preferred parent are delimited through a weighted random selection, according to the score obtained in the evaluation metric of the parent node.
    1.2. The remaining energy value of the nodes is considered for the underlying calculations of the objective function.
2) A new routing metric is available, combining energy considerations and the parent count of a candidate node.

V. WRF-RPL: WEIGHTED RANDOM FORWARD RPL

This section describes the characteristics and operation of the WRF-RPL protocol from the analysis of algorithms and their theoretical foundations.

A. THEORETICAL ASSUMPTIONS

WSN networks can be understood as mathematical models for the description and structure of their behavior from theoretical aspects. Suppose one considers the communications between two devices in a wireless network as a queuing task [34]. In that case, a mathematical model can be established that contemplates the processes and operations involved during this transmission. Queueing modeling poses the sending, receiving, and processing actions as an M/M/1/K system, where the processes are described by probability distributions that are denoted as Markov processes [35].

These probability systems can be modeled using the so-called Kendall notation [36]. This notation describes the actors or agents involved in the queuing system addressed, among which are: arrivals, departures, services, and waiting room capacity. These can be adjusted by particular parameters of the problem, such as the communication system between sensor devices to transmitters. Similarly, this modeling allows estimating and delimiting the probabilities related to sending data between these devices in a WSN, highlighting the buffer size, a parameter directly related to the reception and processing of transmitted messages. In this regard, by contemplating the existing probabilities that describe the communications between two devices in a WSN, a network topology can be described as a system of multiple probabilities of successful reception of messages, considering each P2P communication is an M/M/1/K system. Regarding these statements, it is considered necessary to address the multipath approach (paths considering different neighboring nodes) within the operability of communications protocols, in order to delimit, through queuing considerations, the distribution of messages to be transmitted against the different systems modeled in search of better reception and attention times according to the equations describing this model [36].

B. PROPOSED SCHEME

In scenarios of high traffic and high data demand, limited sensor networks operate at their maximum capacity in order to be able to handle and fulfill the tasks imposed by their design. Therefore, the RPL protocol is oriented to low data rate scenarios, where the sensors present constant hibernation as they do not need to process tasks frequently. Therefore, in demanding scenarios, this protocol presents severe complications in the handling and distributing of the data load to which the network is subjected. Therefore, it is required to address strategies to obtain better results, from the operability of the WSN, in this type of environment where the buffer capacity of the nodes, energy consumption, network lifetime, and packet success rate, among others, are affected to a greater extent.

Among these reasons, the WRF-RPL protocol is proposed considering the multiple communication paths approach for load distribution to guarantee the efficient use of the energy of the sensor network. From the constitution of a metric that considers the remaining energy of a node and the number of parent nodes it has, it is possible to characterize the candidate parents that are part of the ideal path to link communications to a destination. This characterization allows delimiting the scores assigned to each node to determine their priority when performing the weighted random choice, applied from the fundamentals of the proposed scheme.

Regarding how WRF-RPL operates, the contributions and considerations addressed in [12], [14], and [37] are rescued for the proposed load balancing scheme, in which a new network metric is delimited. This metric is chosen to consider the current state of the candidate node in terms of its energy values and the delay alternatives available to the node, as defined in equation 1, where both principles are combined.

$$metric_{evalf} = P_{(remaining\_energy)}(\%) * (P_{(parent\_count)}) \quad (1)$$

From equation 1 of the metric calculation, P is defined as the element representing the current parent under analysis, the attributes describing it as is $P_{(remaining\_energy)}$ which consists of the remaining energy percentage of the node, and $P_{(parent\_count)}$, which consists of the count of candidate parents that a node has. The value of $parent\_count$ value is considered in this metric because the analyzed neighbor node may have multiple possible routes to the sink, which may mean an adequate load distribution among the connections in the communication tree. About the energy consumption of a node, the configuration of this value is left to the researcher's discretion since, depending on the node's capabilities, the energy ceiling may vary. Given the addition of a new metric for evaluating candidate parents, it is necessary to generate modifications in the DIO message transmitted for the discovery of upstream routes. Based on the shared metrics, it is possible to store the information corresponding to the analyzed node, as described in Algorithm 1.

Algorithm 1 Parent Set Construction

```
Data: Parent node $P$ corresponding to a message DIO
Result: Arrangements $parent\_set$, $weight\_set$ y
        $arrival\_set$ updated
$parent\_set \cup P$
$arrival\_set \cup actual\_time(segs)$
$P\_weight \leftarrow P_{(remaining\_energy)} * P_{(parent\_count)}$
$weight\_set \cup P\_weight$
```

Algorithm 1 describes how the protocol acts when reception of a DIO message before analyzing a possible parent candidate (P). The retrieved properties of the message are described, such as the arrival time and the value corresponding to the weight selection metric, which corresponds to the compiled candidate parent's selection metric in the array $weight\_set$. Also, about how the protocol calculates the RANK's value, a parameter of the RPL implementation, equation 2 is described similarly in [11].

$$\mathrm{RANK(n)} = \mathrm{hops(n)} + 1 \quad (2)$$

In 2, we determine the value of the rank of a node n equal to the number of hops that exist between its current position and the sink node, root of the RPL Instance. Let hops (represented in the equation $hops(n)$) as the number of nodes required to communicate with the gateway node n to communicate with the gateway node.

In Algorithm 2, we define how a node performs a next-hop or next-hop selection from the WRF protocol. $preferred\_parent$ from the WRF protocol. It deals with the procedures and decisions taken from the protocol for the weighted random selection by a node that is part of the RPL Instance.

Algorithm 2 Weighted Random Selection

```
Data: A set of candidate parents $parent\_set$ of
      associated weights $weight\_set$, set of parent
      arrival $arrival\_set$, and reception time constant
      $\triangle t$
Result: A selection of preferred parent to next-hop
        $preferred\_parent$
Next jump selection event
$R \leftarrow$ Random value between 1 to 100 to identify the
percentage of choice.
$all\_weight \leftarrow$ Sum of all weights in the array.
$weight\_set$
$current\_time \leftarrow$ Current analysis time, according to the
system clock
$prev \leftarrow 0$ Previous counts of selection probability.
for each $p_i \in parent\_set$,
$w_i \in weight\_set, a_i \in arrival\_set$ do
    if $\triangle t \geq (current\_time - a_i)$ then
        if $(\frac{w_i}{(all\_weight*100)}) + prev \geq R \leq prev$ then
            $preferred\_parent \leftarrow p_i$
            Return $preferred\_parent$
        else
            $prev \leftarrow prev + \frac{w_i}{(all\_weight*100)}$
        end
    end
end
Return $\emptyset$
```

Algorithm 2 can be delimited from the following steps:

Step 1) Explore and analyze the candidate parents that meet the $\triangle t$ criterion. After this filter, we proceed to delimit the weight of each parent, based on its influence percentage in the total sum of the metric of each candidate parent.

Step 2) Once the parents' weights are available, a weighted random selection will be performed. This selection consists of generating a random coefficient that identifies to which percentage it belongs if it is located within the range of influence (compared to the total sum of the weights) of a candidate parent.

Step 3) When the candidate parent is chosen, it is stored for future communications until the elements of the $parent\_set$.

The proposal avoids congestion resulting from poor load distribution by distributing the probability of choice among the candidate parents. It is sought to converge to selecting alternative routes with sufficient energy and a higher load relaying option (higher $P_{(parent\_count)}$).Concerning the actions that describe the operation of the WRF-RPL protocol, Figure 3 shows the flow of the processes underlying the analysis and decisions taken when a sensor node receives a packet.

From Figure 3, we can identify the importance of the reception of the DIO packet and the subsequent selection of $preferred\_parent$. The latter process follows the conditional that directly influences how control messages are

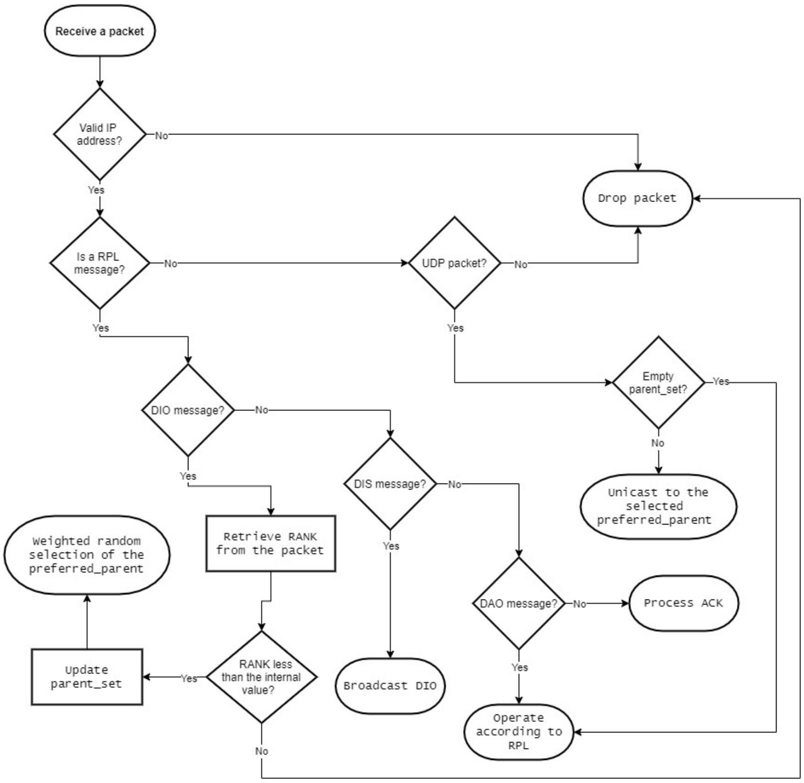

FIGURE 3. Flow chart of the WRF-RPL protocol.

transmitted during the network's lifetime. The conditional consists of identifying whether, from the candidate parents, a *preferred_parent* has been chosen with a higher relevance or weight (using Algorithm 2), with the purpose of chosen as the "global parent" and informing it using DAO messages. If the opposite is the case, the WRF-RPL protocol does not perform any additional action since the *preferred_parent* chosen will be of internal knowledge and not of the topology. This not informed hop is considered as an alternative or local route, as opposed to the one reported to the DODAG, which corresponds to a route of global knowledge.

C. BEHAVIOR OF THE PROTOCOL OVER WSN

The operation and deployment of the protocol described above can be observed in a specific example. Figure 4 describes an example of how the assignment of weights and their respective probability of selection can be delimited (related to Algorithm 2). For example, nodes with a higher number of parents or hops are more likely to be selected than others.

One situation of the scenario presented in Figure 4 comes from how the paths are selected, as shown in Figure 4.b and Figure 4.c. In these schemes, nodes E and D send packets to the sink node using routes defined by OF. This communication presents a hop at node C, which will make the balancing decisions according to the probabilities proposed for the connections. Therefore, it is evident that it makes two different forwarding decisions in both cases. Figure 4.b node E sends a packet to the ROOT through its single candidate parent C, which randomly selects node B as the next hop with a 70% probability of choice. As for Figure 4.c, node D sends a packet to the sink via nodes C (30% chance of being chosen) and A, which has a similar 30% chance of being selected. The load distribution is sought through highly probable routes, meaning with a better metric value, or through unlikely routes, but equally likely to be chosen (principle of weighted randomness) to relieve the connections that make up the network.

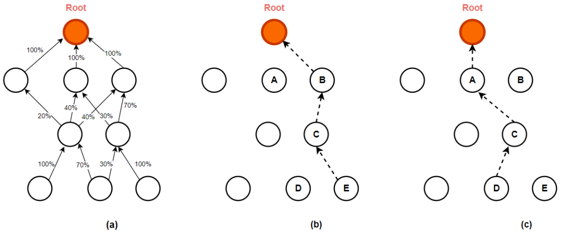

FIGURE 4. Example of assignment and forwarding through candidates' parents.

VI. EVALUATION

For evaluating the proposal, the well-known Cooja [38] simulator/emulator of the Contiki [39] operating system for restricted devices was used. This simulator allows the construction, communication, and operation of the proposed balancing protocol to be staged by emulating its behavior in a mesh of distributed nodes. For the test scenarios, a design of multiple devices or nodes in an area of 200 × 200 meters with random positioning of the nodes is proposed, except for the sink node, located on the right side of the scenario to fulfill the data collection tasks. Similarly, the protocol is expected to be subjected to different situations, so simulations present varying the number of nodes that make up the topology (30, 75, and 100), presenting an equal rate of sending data packets (40 packets per minute). It is also expected to validate a topology at different rates (20, 40, 80, and 100) of packets sent per minute (ppm - packet per minute). This last test allows subjecting the simulated WSN topology to high data flow scenarios, i.e., congested scenarios that will identify the reliability, efficiency, and benefits of the proposed load balancing proposed in this research. Other parameters and configurations arranged for the staging of the simulated WSN topologies are described in Table 1.

TABLE 1. Simulation configuration.

Parameter	Value
Number of sensor nodes	30, 50 and 100
Simulation time	Until the first node dies (maximum 25)
Coverage area	200 x 200 meters
Data sending rate	40 ppm and variable rate tests of 20, 40, 80, and 100 packs/minute
MAC/ adaptation layer	Contiki MAC/ 6LowPAN
Initial energy of a source node	9 J
Type of mote used	Tmote Sky
Buffer size	8 packages
Distance loss	90% RX radius
Transmission range	70 meters

In how many of the established analyses, we seek to compare the WRF-RPL protocol with ETXPC-RPL [16], lbRPL [23] and MRHOF [40] under the metrics of (i) the network lifetime, which refers to the time at which the first node in the topology dies, i.e., reaches its energy cap and stops operating within the sensor network [41]; (ii) the RPL message overhead, which refers to the number of ICMPv6 packets sent in the network, such as DIO or DAO messages, used for topology control and network maintenance and (iii) the PDR which refers to the number of packets that are successfully received by the sink node. Regarding energy considerations, since the implementation of the protocol in Contiki, it was required to estimate each node's energy consumption in the network. This implementation was possible using the operating system's libraries and the energy model adaptable to the hardware architectures used, as shown in equation 3.

$$\begin{aligned}\text{Energy(mJ)} &= (\text{Transmit} + \text{Listen} \\ &\quad + \text{CPU\_time} + \text{LPM})\text{mA} * \text{Voltage} \quad (3)\end{aligned}$$

The model described in 3, which is based on that presented in [42], describes an individual node's consumption after a certain period. This time corresponds to the time elapsed between the node power-up and the report made on its current consumption status. Each variable in the model has the following purpose:

1) Transmit, which describes the consumption by the node's transmitting action.
2) Listen, which refers to consumption in the receiving state.
3) CPU, which represents the cost of processing the logical actions.
4) LPM, which describes the state transition from hibernation to power-up by the nodes.
5) Voltage, which is the current necessary for the ignition of a mote.

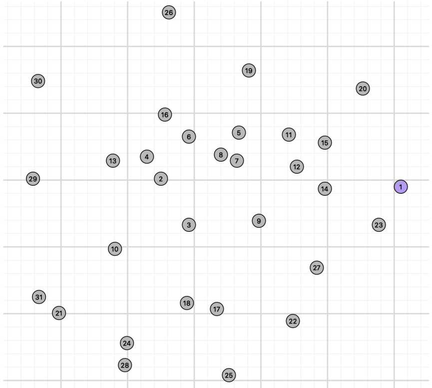

FIGURE 5. Network topology with 30 sensors nodes.

These metrics are defined by the time per unit cost of the task, described in the corresponding datasheet of the actual selected device for the simulations. Considering these calculations, Figures 6, 7, 8 and 9 delineate the results under different data rates in preset network topology (Figure 5). Figures 10, 11, and 12 show the comparisons under different WSN topologies, varying the number of nodes that compose them.

Among the first analyses established, the one corresponds to the network lifetime, which identifies the moment in which the first node of the network consumes its energy (9 Joules limit for these scenarios). From figure 6, it can be concluded that by implementing the WRF-RPL protocol, it is possible to extend the Network Lifetime, compared with the standard RPL protocol. When comparing WRF-RPL with other protocols that consider load balancing important, it can be seen that WRF-RPL is better in most cases. The WRF-RPL performance is better considering that the data transmission rates imply a demanding scenario, and the equitable distribution of the retransmission tasks is critical. As a conclusion, it can be stated that WRF-RPL and lbRPL are proposals that guarantee load distribution to extend the network's life. For the analysis of other metrics, a network execution time limit must be established once the first node is lost due to the topology and its behavior. All this since there is a disconnection within the communications scheme of the sensor nodes conforming to

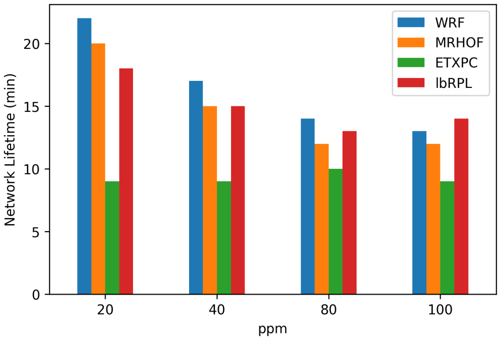

FIGURE 6. Network lifetime analysis on different data flows.

the network. Therefore, the subsequent analyzes are established until the moment in which the lowest Network Lifetime is reached, resulting from the protocols that are part of the comparative analysis. In this case, the ETXPC protocol has the worst performance in Network Lifetime (the time interval determines the subsequent analyses of this first test scenario).

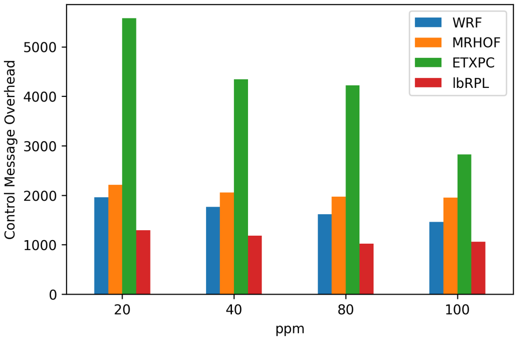

FIGURE 7. Overhead of RPL messages analysis on different data flows.

Regarding the analysis of control messages (Figure 7), there are significant differences between the evaluated protocols, which again describes the ETXPC protocol as the protocol with the worst performance. Regarding the instability present in the network, WRF-RPL presents better performance than ETXPC and standard RPL with differences of approximately 50% and 20%, respectively. This improved performance is because the proposed scheme has changed the parent only when there is a decrease in the chosen global parent metrics. lbRPL is described as a protocol that avoids network overhead. However, sending many packets increase the number of control messages required for its operation and is presented with the worst behavior in this scenario. In this way, it is reported to a lesser extent than in RPL despite being in the stable network simulation (RX at 90% probability of successful packet reception), requiring flooding the network more frequently.

Also, one of the evaluation metrics mostly employed in this kind of validation of RPL-based schemes [40], [41], corresponds to the PDR (Figure 8). The hypothesis of better performance from the WRF-RPL is fulfilled regarding the obtained results. Concerning the comparison with protocols oriented to balancing, WRF-RPL is the one that presents the best results, consisting of a 15% improvement in the average number of successfully received packets in the different scenarios than MRHOF, 25% on average with ETXPC, and 26% on average with lbRPL. This improvement happens when considering alternative communication routes, which in addition to avoiding possible congestion of preferred parents, allows having routes that guarantee the successful reception of packets. The factors that can influence the ETXPC and lbRPL protocols present worse performance than MRHOF because the metric and composition of the parent choice metrics may be inadequate or very complex under high-demand scenarios.

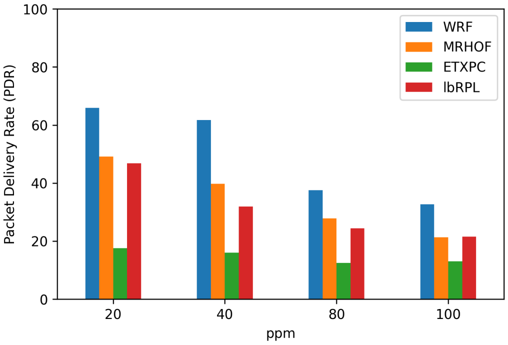

FIGURE 8. PDR analysis on different data flows.

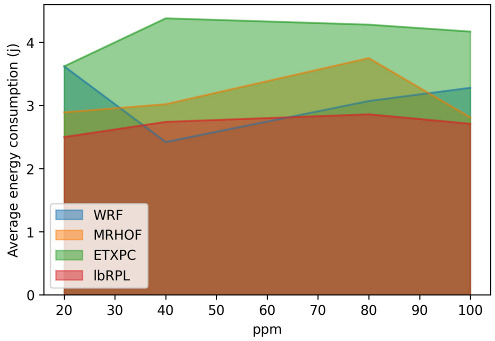

FIGURE 9. Energy analysis different data flows.

Figure 9 shows the average consumption of each of the protocols in the different test scenarios regarding the energy consumption analysis. In this case, WRF-RPL and lbRPL are the best performers in simulation scenarios with an average consumption of less than 4 J, considering that the networks' simulation time does not exceed 15 minutes, taking into account the Network Lifetime interval selected. EXTPC and MRHOF present variable behaviors in energy consumption, possibly related to their behaviors in other metrics such as the overhead of control messages originating in the network. On the other hand, even though WRF-RPL may present consumption values higher than lbRPL, the more significant number of packets received by the sink, the retransmission

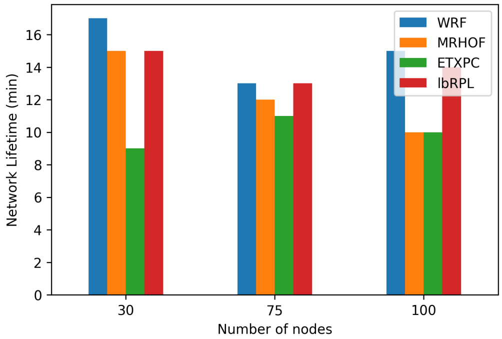

FIGURE 10. Network lifetime analysis on different nodes number.

tasks are adequate and allow the network to achieve its data collection objectives. The consumption results are presented in the 40 ppm scenario, where WRF-RPL successfully transmits twice the number of packets that lbRPL has received since its implementation.

Regarding the validations with node variation, Figure 10 shows the network lifetime under different topologies. This graph shows an extension of the lifetime by WRF-RPL over MRHOF, ETXPC, and lbRPL, with differences not more significant than 5 minutes in each scenario (30, 75, and 100). These results, being directly dependent on the arrangement of the nodes in the topology, show variations in their results, thus giving an approximate picture of their behavior. Similarly to Table 1, a cloud of nodes is placed around the census area to identify the communication protocols' behavior. In this case, it can be identified that increasing the number of nodes extends the network lifetime using the WRF-RPL protocol compared to the standard RPL protocol. WRF has a more significant number of alternative connections for effective load distribution, thus relieving possible congestion.

Also, the results regarding the PDR in the simulated scenarios are described. It is highlighted that results presented are up to the simulation minutes 9, 11, and 10, respectively, considering the metrics' analysis according to the shortest lifetime between both protocols.

Figure 11 shows the expected behavior between the comparative protocols; as the network is in a demanding data flow (40 ppm), it must distribute data through strategic and contextualized retransmissions of the network status. Also, there is a considerable decrease in the success rate as the number of nodes increases. For this kind of topologies, it may be necessary to have an architecture that considers more than one sink node. As for the advantages of implementing the WRF-RPL protocol, there is evidence of a PDR higher than 11% on average compared to the standard RPL protocol and 24% compared with ETXPC, which is a significant improvement when considering the system requirements.

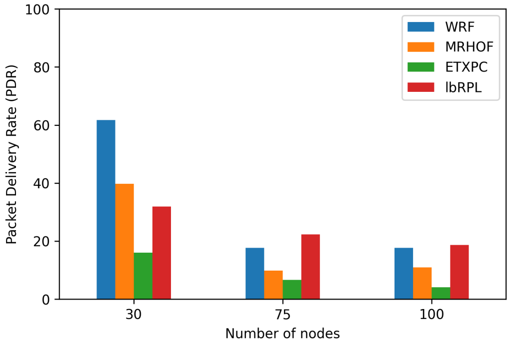

FIGURE 11. PDR analysis on different nodes number.

Obtained results about average energy consumption show the influence of having a more significant flood of packets when nodes are added to the topology (figure 12). The results presented show that they generate greater consumption than in the previous scenario. Similarly, WRF-RPL and lbRPL maintain the trend of presenting less than 4 joules of energy consumption due to their balancing schemes that distribute this consumption around the nodes in the topology.

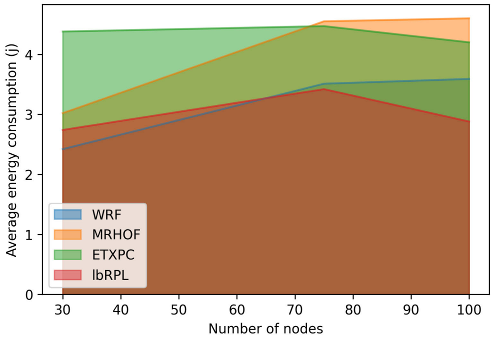

FIGURE 12. Energy analysis different nodes number.

Another possible inference from the simulations performed is the evident difference between the results described in the topologies with 75 and 100 nodes. There is a better performance in topologies with 100 nodes, despite the increase in the number of devices. Starting from how these nodes are arranged (Figure 13 and 14), it is evident that in the 100-node topology, there is a cloud of intermediate nodes or nodes that can be larger relays, as opposed to the 75-node topology, in which there is a more significant number of leaf nodes (nodes without children).

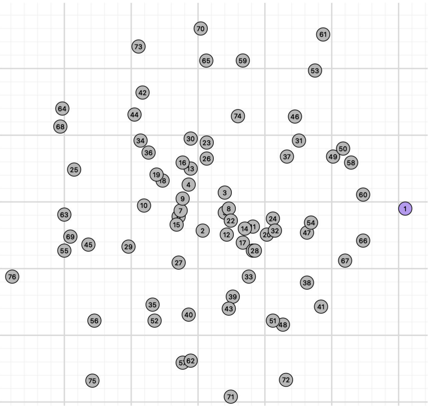

FIGURE 13. Network topology of 75 sensor nodes.

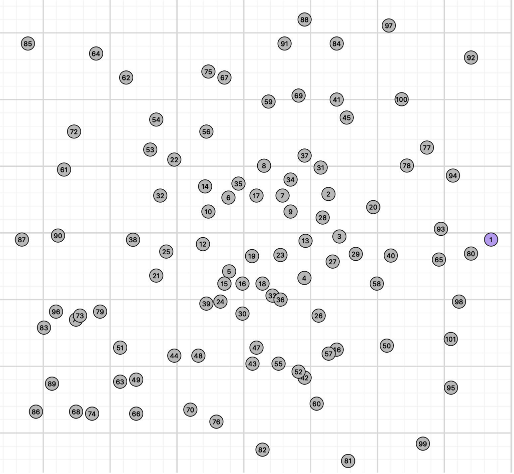

FIGURE 14. **100 sensor node network topology.**

From figure 14, it possible to establish the premise that the more intermediate nodes there are in the network, the better the load balancing of the proposed scheme works. This improvement is because by having a more significant number of candidate nodes to be relay or parent nodes, it is possible to obtain an efficient load distribution. This behavior is different from that described in the MRHOF function results, where a decrease in the evaluated metrics is evidenced as the number of nodes in the simulation increases.

VII. CONCLUSION AND FUTURE WORK

This paper presents the WRF-RPL protocol, oriented to load balancing in sensor networks with high traffic. As a solution to the balancing problem present in RPL when operating in demanding scenarios in a data flow, the proposal is delimited according to the paradigm of multiple transmission paths and the composition of two metrics, such as the remaining energy and the count of parent nodes. Different scenarios of topologies with a single sink node and high data traffic have been considered. The performance evaluation of the proposed protocol has been simulated using Cooja on different test scenarios with variations in the number of packets per minute and the number of nodes in each topology. The results reflect that the proposed WRF-RPL outperforms the standard RPL protocol with the MRHOF objective function ETXPC, in terms of network lifetime metrics, by keeping all the topology operating nodes longer time. In terms of RPL message overhead, in most cases, the proposed protocol requires fewer control messages to accomplish the communications tasks; in terms of successful packet sending, it has a higher percentage of packets received by the sink node. The improvements in the evaluated metrics are directly related to the number of relay nodes in the initial topology since the more nodes that can perform relay tasks, the better the load distribution with the WRF-RPL function. As for the comparisons with lbRPL, the proposed protocol improves Network Lifetime and PDR in most cases. Being lbRPL one of the protocols that present better results in some of the tests allows inferring both proposals' efficiency in load balancing in WSN. As future work, we seek to test different network topologies such as heterogeneous or mobile networks to address the multiple applications of WSNs.

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PEDRO DAVID ACEVEDO is currently a Systems Engineer and a Magister (C) with the Universidad del Norte, Barranquilla, Colombia. His research interests include wireless sensor networks, graph theory, software development in educational context, and cryptography.

DALADIER JABBA received the degree in system engineering, the M.Sc. degree in computer engineering, and the Ph.D. degree in computer science and engineering from the University of South Florida, Tampa, FL, USA, and the M.Sc. degree in computer science from UNAB, Colombia.

He is currently an Associate Professor with the Department of Systems Engineering, Universidad del Norte, where he is also a member of the Research Group on Computer Networks and Software Engineering (GReCIS). Before joining the Universidad del Norte, he belongs to the Research, Development and Innovation Department, as an International Resources Manager (R&D). He has published more than 40 articles in different journals and ten publications between books and book chapters. He works in the projects of University-Industry Interaction, and he has belonged to the National Committee that designs templates in order to develop the questions in the tests named Saber Pro for students of final semesters in Colombian universities. He was part of the group of researchers belonging to the Technical Secretariat of the Universidad del Norte, supported by the "Mission of Wise Men" appointed by the Colombian Government, in 2019, in the focus of Industry 4.0.

PAUL SANMARTÍN received the Ph.D. degree in computer science from the Universidad del Norte. He is currently a Research Professor with Universidad Simón Bolívar. His areas of interests include Quality of Service on the Internet, the IoT, WSN, routing protocols, NGN, and telematics applications.

SEBASTIÁN VALLE is currently a Systems Engineer and a Magister (C) with the Universidad del Norte, Barranquilla, Colombia. His research interest includes wireless sensor networks.

ELÍAS D. NINO-RUIZ received the Diploma degree in system engineering, the M.S. degree in system engineering, and the M.S. degree in industrial engineering from the Universidad del Norte (UniNorte), Barranquilla, Colombia, in 2007, 2009, and 2010, respectively, and the Ph.D. degree in computer science and applications from Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA, USA, in 2015. He worked as an Intern at the Argonne National Laboratory, USA, in 2013, and the Lawrence Livermore National Laboratory, USA, in 2014. He served as a Research Assistant with the Computational Science Laboratory (2011–2015) and as an Instructor of Numerical Methods at Virginia Tech, in 2015. In 2016, he joined the Department of Computer Science, UniNorte, where he works as an Associate Professor, the Chair of the Department of Computer Science, and the Director of the Applied Math and Computer Science Laboratory. His research interests include the areas of computational science, applied mathematics, and applied statistics.

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