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Optimization of Parent-node Selection in RPL-based Networks
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Abstract

This document describes the problems in the DODAG construction of RPL-based network including "Thundering Herd" problem and Randomly Unbalanced Networking. The corresponding optimization methods are proposed to improve balancing the selection of parent nodes.

Status of this Memo

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1. Introduction

IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) is a route-over distance vector routing protocol for networks in constrained conditions such as limited power and bandwidth. This protocol defines a Destination Oriented Directed Acyclic Graph (DODAG) to avoid the emergence of loops in the network [RFC 6550]. The routing procedure is based on an objective function (OF) including a set of metrics/constraints. The selection of the parent node in the RPL-based network directly influences the networking balance, and particularly, a poor balance causes the frequent switches of parent nodes. During the switching process, the delayed communication directly affects the stability of the entire network, so networking balance is an important indicator of the stability of mesh network.

In the RPL-based mesh network, due to the lack of balance algorithm, a large batch of nodes possibly select the same parent node and leave others empty, turning this focused parent node to be a forwarding point. A higher rate of transmission failure will result in a sharp increment in RANK, which triggers all child nodes to re-select and switch their parent node, and so on, causing frequent switching of the parent node. This phenomenon is particularly frequent at the beginning of networking that greatly decrements the efficiency of networking and communication stability. Therefore, the mechanism to select the parent node, making 6LoWPAN reach a balanced mesh network, is an urgent problem to be solved.

This document points out the problems associated with the RPL-based

networking, and proposes solutions for optimizing the balance of parent selection problems. Modifications are incrementing the RANK default value and introducing a new metric called "Child Node Count".

1.1. Requirements Notation and Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

Below are the terms used in this document:

6LBR: 6Lo Border Router

6LN: 6Lo Node

CNC: Child Node Count

DAO: Destination Advertisement Object

DIO: DODAG Information Object

ETX: Expected Transmission Time

MOP: Mode of Operation

MRHOF: Minimum Rank with Hysteresis Objective Function

OP0: Objective Function Zero

RSSI: Received Signal Strength Indicator

2. DODAG Construction and Objective Functions

In general, an RPL-based network consists of three types of nodes: root node, connecting to another network as a gateway; router, forwarding topology information and data packets to their neighbors; leaf node, only joining a DODAG as an end member. The construction of a DODAG starts at the root node, through the routers, down to the leaf nodes. The root node broadcasts to its sub-nodes the DODAG Information Object (DIO) messages that contain the RANK information. Once receiving DIO messages, a sub-node chooses the node with the minimum RANK as its appropriate parent node. Afterwards, the routers will compute their own RANK according to the Objective Function (OF), update the DIO message, and forward to their neighbors.

Objective Function Zero (OF0) is designed as a default OF that allows

interoperation between implementations in a wide spectrum of use cases [RFC 6552]. OF0 specifies that a node calculates its own RANK R(N) according to the following equation:

R(N) = R(P) + rank_increase   (1)

where rank_increase = (Rf * Sp + Sr) * MinHopRankIncrease (Rf, Rank_Factor; Sp, Step_of_Rank; Sr, Stretch_of_Rank). R(P) is the RANK of the parent node.

Apart from OF0, the Minimum Rank with Hysteresis Objective Function (MRHOF) is another OF that selects routes that minimize a metric. One common metric used in OF is the Expected Transmission Count (ETX), indicating the number of transmissions a node expects to make to a destination in order to successfully deliver a packet [RFC 6551]. When MRHOF uses ETX as its metric, nodes locally compute the ETX of links to its neighbors and add this value to their advertised Rank to compute the associated Rank of routes [RFC 6719]. In this case, the calculation of RANK can be simplified to be equation

R(N) = R(P) + ETX(N) * 128   (2)

where ETX(N) is the ETX of links to its parent node. The ETX value normally follows an update formula

ETX = ETX_Old * 0.9 + ETX_New * 0.1   (3)

where ETX_Old is the previous ETX value, and ETX_New is calculated by ETX= 1 / (Df * Dr) in which Df is the measured probability that a packet is received by the neighbor and Dr is the measured probability that the acknowledgment packet is successfully received [RFC 6551]. Once a node joins an RPL network with a default value ETX(N), e.g. 1*R, the ETX gradually converges to the actual value after several times of update.

3. Problems with Current DODAG construction

3.1. Problem 1: "Thundering Herd" Phenomenon

When a node joins the RPL-based network (such as 6LN_New in Figure 1), the transmission path may be better than other nodes because the Default_Rank_Increase is 3*256, calculated by equation (1) with the following default values specified in [RFC 6552]:

DEFAULT_MIN_HOP_RANK_INCREASE = 256

DEFAULT_STEP_OF_RANK: 3

DEFAULT_RANK_STRETCH: 0

DEFAULT_RANK_FACTOR: 1

Suppose the RANK of 6LN in Figure 1 is much higher than 4*256 and meets the requirement of parent switching when 6LN_New joins. Then once 6LN_New broadcasts the DIO messages including the RANK value of 4*256 (1*256 for Root_Rank; 3*256 for Rank_Increase), it may trigger a switch of numerous child nodes (circles in Figure 1) from their original parent nodes. Note that the dashed box depicted in Figure 1 is the common coverage of 6LN and 6LN_New. So once a new node joins a network with a small RANK default value, it may suddenly attract numerous sub-nodes, impacting on the stability of the network. This phenomenon is called "Thundering Herd".

```
                 6LBR
                  /\
                 /  \
                /    \
              6LN     \
              /|\   6LN_New
             / | \    /|\
          + - - - - - - - - - +
          | o o o o o o o o | Numerous
          |   o  o o  o  o  |
          |  o  o   o  o  o |   6LNs
          | o   o    o    o |
          + - - - - - - - - - +
```

Figure 1: Example of Network Topology of "Thundering Herd"

3.2. Problem 2: Randomly Unbalanced Network

Although the RANK in DIO messages reflects various features of the network quality (e.g. Hop_Count, Latency, ETX), there is another issue waiting to be solved: balancing the parent selection among nodes with the same RANK value. Currently in this case a node randomly chooses one as its parent node from the candidate parents with the same RANK, which gives the possibility of unbalanced networking. As depicted in Figure 2, the RANK of node A, B and C are supposed to be equal, but node B by chance dominates in the number of child nodes even though they share the common coverage (dashed square). It is a waste of resource that Node A is left empty while reachable for the sub-nodes. After a long period of time, the network only achieves a relative balance which is easy to be broken when new nodes join in.

This problem is particularly serious when the unbalanced networking

happens near the root node and above a large number of sub-nodes. Suppose in Figure 2 there are numerous child nodes connected to node D, E, F, G, and H, which put high load pressure on node B and C. In this case, overload and traffic block are likely to happen near the root, which further forces the network structure conversion. Node D, E, F may switch their parent node after network reconstruction but the best solution is achieving a balance in the parent selection at the beginning of the networking.

```
                                6LBR
                                 /|\
                                / | \
                               /  |  \
                              /   |   \
                             A    B    C
                           + - - - - - - +
                           |     /|\  /| |
                           |    / | \/ | |
                           |   /  | /\ | |
                           |  D   E/  F| |
                           |      /    | |
                           |     H     G |
                           + - - - - - - +
```

Figure 2: Example of Randomly Unbalanced Network Topology

4. Optimized Solution

4.1. Solution 1: Increment the ETX_Initial value

In order to reduce the impact of the Thundering Herd phenomenon in the network, the Default_Step_of_Rank value defined in OF0 SHOULD per this document be incremented to

DEFAULT_STEP_OF_RANK: 4

So the Default_Rank_Increase is 4*256, and then based on the actual transmission result, the RANK gradually approaches the actual value. In this way, a new node joining the RPL network is initially set to be with a larger RANK default value. If transmissions through this node are of high quality, the RANK of this node will decrement gradually and attract child nodes one by one, which reduces the appearance of the Thundering Herd phenomenon. It is worthwhile noting that this solution is particularly applicable for the scenarios with numerous nodes and high node density.

This modification is also suitable for the MRHOF. Take ETX metric for an example: the default ETX(N) according to the modification

SHALL be set to 8, which gives R(N) = R(P) + 8*128 according to equation (2). The high initial RANK lowers the possibility of Thundering Herd phenomenon while afterwards the RANK gradually converges to the actual value according to equation (3).

4.2. Solution 2: Introducing the Child Node Count Metric

In order to optimize the randomly unbalanced networking, this document proposes a method: introducing the number of child nodes as a new metric/constraint in the DAG Metric Container, which can be included in the Option field in the DIO message. The newly added information is 2 octets named by Child Node Count (CNC) which is per this document defined in the DAG Metric Container. The Routing Metric/Constraint Type is per this document RECOMMENDED to be value 9.

The Child Node Count (CNC) object is used to provide information related to the number of child nodes in the DIO source node, and may be used as a metric or as constraint.

The CNC object MAY be present in the DAG Metric Container. There MUST NOT be more than one CNC object as a constraint per DAG Metric Container, and there MUST NOT be more than one CNC object as a metric per DAG Metric Container.

The format of the CNC object body is as follows:

```
 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  (sub-object) .....
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: Child Node Count Object Body Format

```
 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      CNC      |    MAX_CNC    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4: Child Node Count Sub-Object Format

CNC: 8 bits. The Child Node Count is encoded in 8 bits in unsigned integer format, expressed in number count, representing the number of child nodes.

MAX_CNC: 8 bits. The Maximum Child Node Count is encoded in 8 bits

in unsigned integer format, expressed in number count, representing the maximum number of child nodes allowed in the neighbor cache.

The CNC field gives the number of child nodes while together with the MAX_CNC field, sub-nodes are able to know the capacity of the candidate parent nodes, minimizing the need of NACK messages. The CNC object may be used as a constraint or a path metric. For example, one may want the CNC not to exceed some value. In this case, the CNC object common header indicates that the provided value relates to a constraint. In another example, the CNC object may be used as an aggregated additive metric where the value is updated along the path to reflect the number of child nodes along the path.

To solve the Randomly Unbalanced Network addressed in problem 2, this document proposes a optimization: using a combined metrics of ETX and CNC in the parent selection process. In this method, Prec field in the Routing Metric/Constraint Object is used with the following precedence: ETX > CNC, e.g. Prec of ETX is set to 0 and Prec of CNC is 1. In this case, the DAG Metric Container carries two Routing Metric/Constraint objects: one is an ETX metric object with header (C=0, O=0, A=00, R=0) and the second one is a Child Node Count object with header (C=0, O=0, A=00, R=0). Since Prec of ETX is set to be 0, which gives a higher priority, then nodes first choose the candidate parent nodes with the best link quality according to ETX. Afterwards, among the candidate parent nodes, the node with minimum CNC is selected to be the parent node. Note that this method is applicable for the storing mode of operation in which the nodes stores the information of their neighbors and thus are able to calculate the number of child nodes. In addition, when the candidate parent nodes contain both the same ETX and CNC, the child node SHOUD randomly choose one as the parent node among them.

This method is applicable for the storing mode of Mode of Operation (MOP) in which the Destination Advertisement Object (DAO) message is unicast from the child to the selected parent(s). For the non-storing mode, the CNC metric/constraint SHOULD NOT be used in the DIO messages, or if used, the CNC value MUST be set to 0. It is worthy to note that [draft-jadhav-lwig-nbr-mgmt-policy-00] gives a conceptual idea of this method in its section 2.5.3 while this document proposes the standard method to solve the unbalanced networking problem.

In the wireless networking scenarios, it would be better to take the wireless signal strength into consideration in the parent selection process, otherwise the optimally balanced network may lead to worse network communication quality for some child nodes. The wireless signal strength can be quantified by the Received Signal Strength Indicator (RSSI). This element can be added in the parent selection

process with the priority: ETX > RSSI > CNC. Note that the selection in the RSSI processes are not to choose the best value but to filter out candidate parent nodes according to the ranges (e.g. -80dB < RSSI <20dB). The RSSI value can be measured by the child nodes thus no additional modification is needed in the DAG Metric Container. So the parent node selection in wireless mesh networks can be processed as follows: Nodes in the network obtain the identity of candidate parent nodes, the number of child nodes, and the RANK. A filtering process takes place in the candidate parent nodes based on the identification and the RANK. Then these candidate parent nodes are filtered again according to the wireless communication quality index, RSSI. Finally, the candidate parent node with the minimum number of child nodes is determined as the target parent node in the network. Note that the RANK of each candidate parent node is the average value based on the current ETX, which is set to be greater than the default path coefficient R. The RANK of a node describes the total path to the border router (BR), which is determined by the RANK of the parent node together with the current ETX.

5. Security Considerations

This document has no security consideration beyond those in [RFC 6550], [RFC 6551], [RFC 6552] and [RFC 6719].

6. IANA Considerations

This document creates an IANA registry for the Routing Metric/Constraint Type. The assigned value is shown below in comparison with the existing values:

Value	Meaning	Reference
1	Node State and Attribute	RFC6551
2	Node Energy	RFC6551
3	Hop Count	RFC6551
4	Link Throughput	RFC6551
5	Link Latency	RFC6551
6	Link Quality Level	RFC6551
7	Link ETX	RFC6551
8	Link Color	RFC6551
9	Child Node Count(*)	This document

7. References

7.1. Normative References

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7.2. Informative References

[draft-jadhav-lwig-nbr-mgmt-policy-00] Jadhav, R., Sahoo, R., Duquennoy, S., and J. Eriksson, "Neighbor Management Policy for 6LoWPAN", draft-jadhav-lwig-nbr-mgmt-policy-00, January 2017, <https://tools.ietf.org/html/draft-jadhav-lwig-nbr-mgmt-policy-00>.

[RFC6551] Vasseur, J., Kim, M., Pister, K., Dejean, N., and D. Barthel, "Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks", RFC 6551, March 2012, <http://www.rfc-editor.org/info/rfc6551>.

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