SEEOF: Smart Energy Efficient Objective Function

Adapting RPL Objective Function to enable an IPv6 Meshed Topology Solution for Battery Operated Smart Meters

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***Abstract*— In this research, a new Smart Energy Efficient Objective Function (SEEOF) is designed to develop an IPv6 meshed topology for IoT based smart metering applications. IoT protocols offer horizontal scalability, interoperability and multi-service environment versus isolated, proprietary and service based environment of traditional smart metering network solutions. Smart metering is not limited to electricity meters; it comprises gas and/or water meters. In other words, it encompasses battery powered devices with limited computing functionalities and energy resources along with full functional devices powered by main line. The battery consumption of end-points is a major challenge and should be addressed in IoT smart-metering solutions. Among the various techniques to reduce the energy consumption, routing is a key element affecting the network performance and lifetime. IETF in its ROLL working group has considered RPL as the routing protocol for IoT applications in low power and lossy networks (LLN). SEEOF, based on RPL, is designed to use energy efficiently and extend network lifetime. It takes into account both the link quality and node energy. We have implemented SEEOF in ContikiOS and compared the energy consumption in RPL using SEEOF with existing objective function. Simulation results show that up to 27% improvement is attained in the network life time when using the proposed objective function. More importantly, the results show that SEEOF balances the energy consumption more uniformly among the battery powered devices keeping them alive for longer duration.**

Keywords*— *RPL, Objective Function, Parent Selection, Routing, IPv6, Battery powered devices, Energy Efficiency, Smart Metering, IoT-Internet of Things, ContikiOS.

I. Introduction

The Internet of things (IoT) build a world where physical objects sense, communicate and react with one another intelligently with respect to the changes in the surrounding and become active participants in this smart world. IoT has already made some headway in industry, as it is being used for use cases from health care to energy management. The rise of the IoT is the most important advancement in the long evolution of energy management. Smart metering is an interesting use case that could lead to a vast deployment of IoT solutions. It is a game-changing technology that allows the utilities to target large audiences by enabling new services and business opportunities. Utility providers for gas, water and electricity are motivated more and more to deploy smart metering systems. Smart meters not only provide timely and accurate metering information, but have additional features like power outage/fault notification, quality monitoring, on demand changes of tariff and loads, and tampering and energy theft alerts.

Smart metering is not only limited to electricity meters which are Main Line Powered Devices(MLPDs). It involves gas and/or water meters as well which are battery powered devices (BPDs) to form a heterogeneous network. Because of absence of direct main line, safety and regulatory approval issues due to the presence of high line voltage and increase in size and cost burden, water/gas meters rely on the battery. Energy storage is one of the major technical and practical challenge in the emerging IoT based smart metering network tailored for gas/water meters.

Smart-meter networking solutions can be divided into different categories based on their: i) Communication Technology ii) Network Topology and iii) Open-Standard stack versus proprietary solutions. Various communication technologies offer communication solutions for such smart meters, for example: Power Line Communication, Cellular Communication, Wired Networks, and RF Wireless networks.

In the last decade, star topology, combined with long range RF technology based on a proprietary network stack has been the mainstream solution deployed to harvest meter data. In this solution, very similar to cellular networks, a gateway is installed on top of a pole, tower or a high-rise. To achieve long-distance coverage, low bit-rate RF technologies (in the order of 100 bits per second) are embedded in the gateway and at the endpoints. The communication may be unidirectional or bidirectional.

In parallel, there have been considerable advances in meshed sensor networking. Meshed topology provides scalability, self-healing, low powered, flexibility, reliability and reduced network infrastructure cost. Moreover, short-range RF technologies with much higher bit-rates (more than 100kbits/s) can be deployed in this topology. This means more real time data is collected and more service options can be offered than with basic consumption index reading.

Proprietary protocol stacks, tailored for smart metering applications, while usually robust and efficient, when it comes to their inter-operability and openness to other systems, they

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limp. To unravel this issue, many standardization activities in IETF(Internet Engineering Task Force), IEEE and ETSI(European Telecommunications Standards Institute) are in process to provide open standard solutions[1]–[6]. There are dedicated alliances such as Wi-SUN which "promotes the adoption of open industry standards in wireless smart utility networks" [6]. Wi-SUN network is developed as per IEEE Standard 802.15.4e/g [3], [4] that defines PHY and MAC layer specifications. This permits multi-vendor products to interoperate seamlessly.

IPv6, together with wireless mesh, offers some ready solutions for large scale, low power and lossy sensor networks. IP-based devices can connect easily with existing IP networks, providing end to end connectivity. Recent advances in communications have made the IPv6 protocol possible and efficient for the use in LLNs that are constituted by devices compatible with the IEEE802.15.4 standard.

Among the various technologies discussed, this research focuses on the IPv6 Wireless Meshed based IoT solution for smart meter networks. Such network consists of nodes that have various hardware constraints: limited memory size/buffer, processing capability, limited energy, cost and other link constraints like lossy and unstable links. IETF defines such network classes as Low-power and Lossy Networks (LLNs) [1]. An LLN contains several alternative paths towards a destination with different link conditions and energy constraints. It becomes the prominent responsibility for the routing protocol to make a smart decision in selecting the optimal parent and to construct the routes in a single or multi-hop manner. Thus, routing is one of the key factors [7] influencing the connectivity, performance and lifetime of a heterogeneous network, and it is highly dependent on the parent selection algorithm, governed by the Objective Function (OF). IETF in its ROLL (Routing Over Low power and Lossy Network) working group [1], developed an IPv6 Routing Protocol for LLNs (RPL) for sensor networking in order to standardize communication between low powered devices.

In this research, we aim to enable a combined electricity, gas and water smart meter meshed network using open IEEE/IETF protocols in line with a Wi-SUN IoT solution for smart metering and utility networks. To this aim, we propose a new objective function called SEEOF (Smart Energy Efficient Objective Function), adapted for RPL, that can account for the consumption limits of BPDs. RPL standardization [8] offers the flexibility to define objective functions based on use cases, as the OF is decoupled from the core RPL mechanism and the metrics used. We have validated the efficiency of SEEOF on a simulated network using Contiki stack on a Cooja simulator [9].

II. Related Work

RPL is a pro-active, route-over routing protocol. Its core specification is defined in RFC 6550 [8] which works in conjunction with additional RFCs, as in [10]–[15]. RPL forms a tree-like structure called as DAG (Directed Acyclic Graph) which is then subdivided into one or more DODAGs (Destination-Oriented DAGs) that are rooted at a single destination. Each node has a RANK that represents its individual relative position with respect to the root. The RANK is calculated by the OF and the metrics used.

Among the various node and link metrics/constraints defined for RPL [10], evaluation of the RPL [16], [17] shows that the ETX provides better latency and PDR (Packet Delivery Ratio) while consuming less energy. ETX is the expected number of link layer transmissions required to make a successful transmission. It is clear that when the ETX is used as a metric, both lossy and long routes have larger weights, so it takes into account path length (number of hops), the packet loss ratio and the energy consumption during parent selection. However, it does not consider the residual energy and may lead to uneven energy distribution, as a favorite parent along the path may be exhausted faster. Such act may not be noble for the network lifetime and may lead to network partition. Likewise, selecting the parents on the basis of the residual energy only is also not efficient, as it does not consider the path quality and hence could lead to the selection of non-efficient, non-reliable paths. The energy consumption of a node also depends on the number of children that it bears. If more child nodes are attached, more energy will be drained and vice-versa.

A good energy-aware routing algorithms should be able to balance the choice between a path with maximum remaining energy and a path with lowest energy consumption [18]. Likewise, the traffic should be directed in such a way that the energy consumption is balanced among the nodes in proportion to their energy reserves, instead of being routed to diminish the absolute power consumption [19]. Among the various existing energy-aware routing algorithms other than the one for RPL such as MMBCR (Min-Max Battery Cost Routing), MTPR (Minimum Transmission Power Routing), and CMMBCR (Conditional MMBCR), MDR (Minimum Drain rate Routing), MDR, that uses drain rate as a metric, shows superior performance [20], [21]. Thus, drain rate is used as a base metric for this research.

In the scope of RPL, two OFs have been defined and recommended: OF0 (Objective Function Zero) [11] and MRHOF (Minimum Rank Hysteresis Objective Function) [14]. Both OFs work with only a single metric. Neither of them support multiple metrics or their composition which are required to optimize more than one performance aspect at the same time. This seems to be necessary in heterogeneous networks, where both the energy as well as the quality of service requirements need to be optimized. Trakadas and Zahariadis [22] specify some guidelines for designing an efficient composite routing metric as per an application's requirement to work seamlessly with RPL. There are two basic approaches: lexical and additive metric composition. [23]–[26] demonstrate that using the composite metric helps to improve the network lifetime as well as other performance aspects like the packet delivery rate and latency as compared to using only a single metric. Therefore, a new algorithm needs to be adapted for smart meter applications to allow gas/water meters to work in parallel with the meshed network containing electric meters, taking into account both the link quality and node energy in order to gain optimized performance and utilize constrained resources more efficiently. This algorithm would safeguard that optimal path, preventing it from being shattered and allowing the network to degrade gracefully.

III. New Proposed Algorithm: SEEOF

The consumption/drain rate of a node, introduced in [20], [21], is used as a base metric. It depends upon two parameters: the quality of the path and the number of child nodes. If the quality is low, a node obviously needs to transmit more, increasing the energy consumption rate. If more child nodes are connected to it, more energy is drained because it needs to forward the child nodes' packets as well. Using the drain rate, both the energy consumption as well as the quality are taken into account. However, the drain rate is not really sufficient, as the residual energy of the node is not considered. This is because where the drain rates of the two parents remain similar but have different residual energy, the parent with the higher residual energy should be the best parent. So, we use the drain rate with the residual energy of the node to form another metric called the Estimated Remaining Life Time (ERLT) of the node. The following sections explain this procedure.

A. Calculation of Energy Consumption and Residual Energy

The residual energy (RE) of a node is computed by means of a simple state-based linear software energy estimation model [27], where the energy consumption of a node is calculated as the sum of the energy spent in the various states of the transceiver, basically, Transmission (tx), Reception (rx) and Sleep/Idle state (slp). The amount of energy consumed in a particular state 's' of the transceiver (E_s) is formulated as:

$$E_s = \text{time spent}(T_s) * \text{current drawn}(I_s) * \text{Voltage}(V) \qquad (1)$$

The total energy consumption of a node is then

$$E_{con} = E_{tx} + E_{rx} + E_{slp} = T_{tx}I_{tx}V + T_{rx}I_{rx}V + T_{slp}I_{slp}V \qquad (2)$$

As the current drawn in the sleep/idle state is very low, in the range of few micro Amperes, I_{slp} can be ignored. Hence,

$$E_{con} = T_{tx}I_{tx}V + T_{rx}I_{rx}V \qquad (3)$$

If Q_o is the initial energy of the battery, the Residual Energy for a node (RE) is given by

$$RE = Q_o - E_{con} \qquad (4)$$

B. Introduction to ERLT (Estimated Remaining Life Time)

Let, Q_o be the initial energy. At any time, t, E_{con} energy is consumed. If the node is assumed to continue with the current drain rate (m), it can be predicted that the node will deplete at time 'S' as shown by the dotted line in Figure 1, and the estimated remaining lifetime of this node at time t is

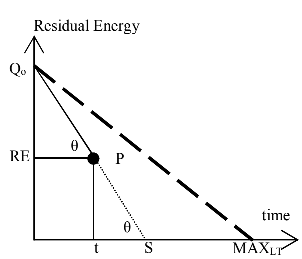

Figure 1: ERLT Calculation

$$ERLT = S - t \qquad (5)$$

From Figure 1, in Δ PtS, the slope which is the drain rate is

$$m = \tan\Theta = (Q_o - E_{con}) / (S - t)$$

Using Eq. (4) and (5), we get,

$$ERLT = RE / m \text{ (in time units)} \qquad (6)$$

ERLT especially helps battery powered devices in parent selection by foreseeing the lifetime of the parent nodes. It is basically a maximizable metric, which means the parent with the higher ERLT is favorable. The ERLT metric is still not enough to provide the full information, as it only provides the information about the parent: a parent's lifetime or energy and its path quality to the root; but it does not provide the information about the link between the parent and the child. This must be taken into account. Hence, parent selection should depend on the ERLT of the parent and the ETX of its link. A new cost function can be developed such that C = f (linkETX, ERLT), explained in detail in Section D.

C. Calculation of linkETX

A non-probing approach is used to calculate the ETX in which the statistics of the previously sent data packets and acknowledgements are utilized. The actual value of ETX is calculated as in [10] and then averaged with exponentially weighted moving average technique in the same way as Contiki:

$$ETX_{rec} = \alpha ETX_{rec} + (1\text{-}\alpha)ETX_{new} \qquad (7)$$

where, ETX_{rec} and ETX_{new} are the accumulated and the new value of ETX, and α (= 0.9 for this research) is the smoothing factor used. This type of relation shows how much contribution is given by the old values to the recent one. It also helps to stabilize the value of ETX in case of any abrupt changes in the link. The same is applied for the relation of the drain rate calculation.

D. SEEOF Cost Function

A cost function represents the cost of selecting a particular parent as the preferred parent. The SEEOF cost function adapts itself according to the type of the parent nodes, and helps to make a smarter parent selection. If the parent is an MLPD, the path cost is the exclusive function of ETX, because the residual energy/lifetime of such parents do not need to be considered. However, when the parent is a BPD, both the link quality (linkETX) with that parent and the lifetime (ERLT) of the parent need to be considered. ETX is a minimizable metric, whereas ERLT is a maximizable metric. With regard to the design considerations to combine two metrics [22], and as suggested by [23], [28], an additive combination technique is used and a new cost function is devised for a SEEOF algorithm for BPDs as:

$$C = [\, linkETX / ETX_{Th} + (MAX_{LT}\text{-}ERLT) / ERLT_{Th} \,] \qquad (8)$$

where, MAX_{LT} is the maximum expected lifetime of a node, ETX_{Th} and $ERLT_{Th}$ are the thresholds for the ETX and ERLT required to switch the parent, respectively. In this function, the ERLT metric is derived into a minimizable metric by subtracting it from a constant maximum value, such as MAX_{LT} - ERLT. By doing so, both ETX and (MAX_{LT} - ERLT) metrics are minimizable and thus can be combined additively.

The cost function thus formed is minimizable. The preferred parent is the one with the lower value of cost C; i.e. lower linkETX and higher ERLT is preferred. This cost function also provides better control over the hysteresis. For example, if ETX is constant between two parents, then the parent switching is done only when the ERLT of one parent is better than the other by $ERLT_{Th}$. Depending upon the requirements, emphasis on the energy/lifetime of the node can be increased by decreasing the $ERLT_{Th}$ and emphasis on the link quality can be increased by decreasing the ETX_{Th}.

E. SEEOF Parent Selection Algorithm

Figure 2 explains the best parent selection process among two parents (P1 and P2) in SEEOF. The first step is to verify the parents' types. Depending upon their types, the parent selection algorithm can be classified into one of the three categories:

a) MLPD and BPD parents
The first case is when one of the parents is MLPD and the other is BPD. An MLPD has infinite energy and thus it is always favored as the preferred parent, but only up to a certain value of linkETX (10 for the simulation).

b) MLPD Parents
The second case is when both parents are MLPDs and thus the parent selection is only dependent upon the ETX. The parent with lower path ETX is selected as the best one.

c) BPD Parents
When both parents are BPDs, parent selection is done by the use of the newly-devised SEEOF cost function (Eq. 8) that considers both linkETX and ERLT. The best parent is the one with the lower value of this cost function.

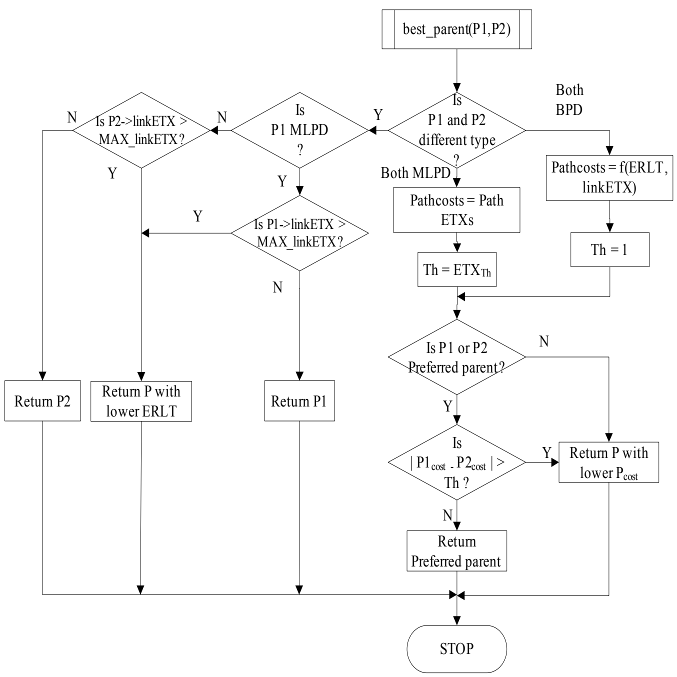

Figure 2: SEEOF Parent Selection Flowchart

The parent selection algorithm continues with a hysteresis function which is applied to keep the preferred parent stable. This avoids any excessive churn produced in parent switching because of minor changes in the metric values. If the difference in the path costs of the two parents is below a certain threshold, where one of the parents is already the preferred parent then, parent switching is skipped. In additive combination, the relative weights/thresholds assigned to the corresponding metrics provide the necessary hysteresis.

IV. Implementation to RPL

Certain assumptions were made while implementing the proposed objective function in RPL as:

- The nodes do not reboot. This assumption is made in order to prevent re-initialization of the variables;
- All nodes start with the same initial Residual Energy and initial drain rate;
- Only Tx/Rx Radio energy consumptions are considered;
- A BPD node has a one-hop child in its sub-DODAG;
- A BPD node does not bear an MLPD child; and
- Network lifetime is the minimum estimated remaining lifetime among all the BPDs in the network [29].

A. Advertising the ETX Metric

As in the MRHOF [14], the ETX metric is carried by the 16-bit RANK field in the DIO(DODAG Information Object) control message. The path ETX is basically calculated as

$$PathETX_j = Rank_i + linkETX_{i\text{-}j}$$

Where, $Rank_i = PathETX_i$

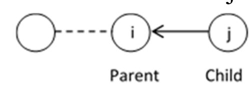

Figure 3: Calculating PathETX

B. Advertising ERLT Metric

ERLT (Estimated Remaining Life Time) is a metric defined specially for BPDs and is advertised by utilizing the optional TLVs of the existing Node Energy (NE) Object [10].

The value of ERLT could not be published in the 8-bit E_E field (2^8=256) of NE Object, as it is insufficient to carry the full ERLT value. With the resolution in hours, 5 years requires at least 15 bits. Thus, a modified NE metric object with an additional TLV is defined and used. Its format is shown below:

<table>
<tr><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>0</td><td>1</td></tr>
<tr><td colspan="4">Flags</td><td>I</td><td colspan="2">T</td><td>E</td><td colspan="8">E_E (Months)</td><td colspan="8">Type</td><td colspan="8">Length</td></tr>
<tr><td colspan="8">Days</td><td colspan="8">Hours</td><td colspan="16"></td></tr>
</table>

Figure 4: A Modified Node Energy Metric Object

'Flags', 'I', 'T', and 'E' represent the same meaning as in the original NE object. Here, ERLT is carried by three 8-bit fields: 'Months', 'Days' and 'Hours'. The 'type' field is assigned to a value 0x64 for simulation purposes. The 'length' field represents the size of the value in bytes, which is 2 in this case.

For an MLPD, the 'T' flag is set to 0 and 'E_E', 'Days' and the 'Hours' fields contain the maximum value, i.e. 0xFF (255). For a BPD, the T flag is set to 1 and E_E, Days and Hours field represent the actual ERLT. With these values, resolution of ERLT is up to hours and the maximum value of ERLT that can be advertised is up to 21 years. Finer resolution, if required by other applications, can be achieved by using additional TLVs.

There are two major advantages for using the existing Node energy object for advertising the ERLT metric. They are:

- No new metric object has to be defined; and
- More importantly, the 'T' flag gives the information about the type of parent (MLPD or BPD) necessary for SEEOF parent selection.

C. DIO Suppression

With regard to [8] and the assumption (iv), the nodes acting as leaf nodes should suppress the DIO transmissions except in response to a unicast DIS message. To implement this, the type of the preferred parent of a BPD node is first checked from the received DIO. If it is MLPD, the BPD node transmits the DIO and can act as a potential router for other BPDs. Otherwise, the

BPD child node suppresses the DIO transmission and the other nodes will not be able to attach to it. This ensures that some energy is gained in the BPD leaf nodes.

V. SIMULATION

Table 1: Simulation Parameters

Simulator	COOJA
Protocol	RPL
Device Model	TMote Sky Node (MSP430+CC2420) [30]
Number of Nodes	18, random position
Radio Medium	Unit Disk Graph Model (Distance Loss)
TX Power	0 dBm
Rx Success ratio	40%, 60%, 80%, 100%
Packet data rate	3 packets/min
Initial Energy Q_o	21024000 mJoules based on 3.65AH,1.6V
ETX_{TH} and $ERLT_{Th}$	192 (1.5*128) and 48 hours
Objective Functions	MRHOF with ETX, SEEOF
Simulation Time	60 hours

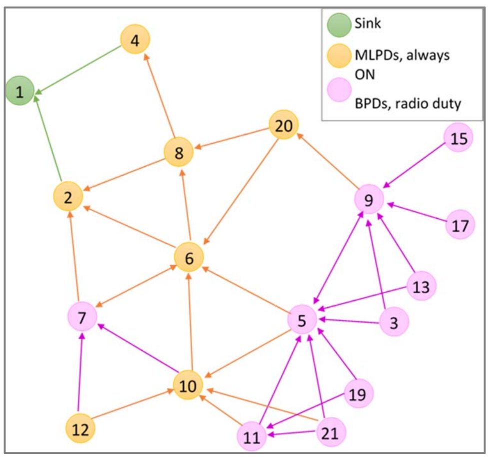

Figure 5: Simulation Topology showing possible parents in COOJA

Cooja with ContikiOS [9] is used as a simulator to evaluate the performance of proposed OF at different Reception(Rx) Success Ratio in RPL. Among the two existing OFs defined for RPL, MRHOF with ETX is used as reference of comparison as it is best suited in terms of energy consumption, latency, PDR and Rank stability [10], [14], [16]. The simulation topology and parameters are defined in Figure 5 and Table 1, respectively. The tree shaped topology is constructed in such a way that all the categories from Section III.E (a, b, c) are included.

VI. RESULTS AND DISCUSSION

The results in the following graphs are from the evaluation of BPDs only. The results obtained are classified as network behavior and router behavior.

A. Network Behavior

It can be observed from the graphs of Figure 6 that with SEEOF, the Packet Delivery Ratio (PDR) is still maintained while improving the network energy consumption and lifetime. From the diagram, it can be perceived that around 23%, 22%, 25% and 27% improvement in lifetime can be achieved for reception success ratios of 40%, 60%, 80% and 100% respectively when using the SEEOF algorithm.

The BPD nodes 5, 9 in Figure 7 have the highest energy consumption, since they act as routers in the network and they need to forward the packets of their child nodes as well. It is interesting to view their behavior as they determine the overall network lifetime.

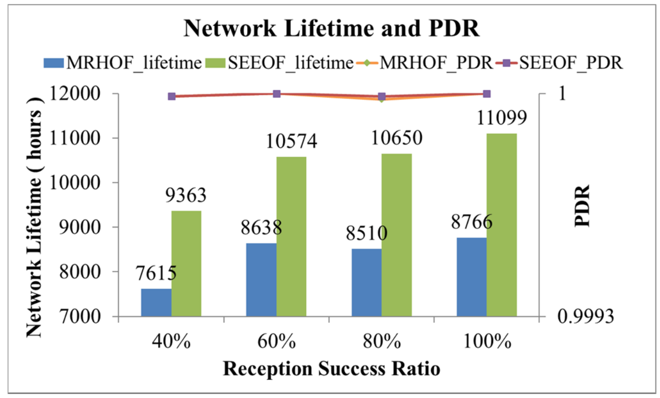

Figure 6: Network Behavior of BPDs at different Rx success ratio

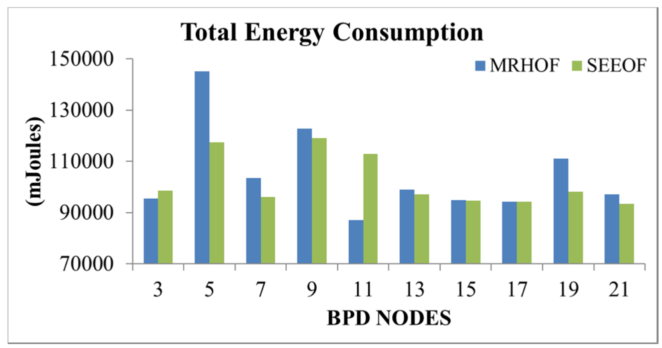

Figure 7: Total Energy Consumption of BPDs at 60% Rx success ratio

B. Router behavior

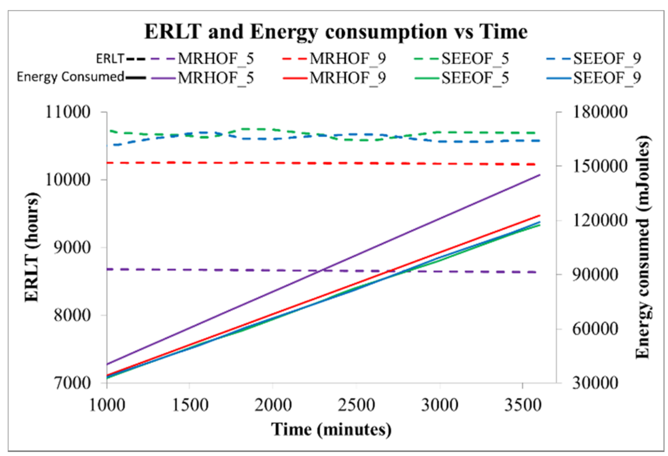

Figure 8: Router Behavior of BPD 5 and 9 between 1000-3600 minutes at 60% Rx success ratio

In MRHOF, which works with ETX only, the leaf nodes tend to use BPD 5 as their preferred parent more often as the path ETX from BPD 5 can be as low as 3 than that from BPD 9 or 11(path ETX low as 4). As a result, the energy consumption of BPD 5 is higher in MRHOF. This can be witnessed from Figure 7. BPD 11, while it is a possible parent candidate, does not have any child attached and thus has a lower energy drain in MRHOF.

However, this gain comes with a higher energy cost to node 5, affecting the entire network's lifetime. On the contrary, in SEEOF, which takes both link quality and energy into account, energy consumption is much more balanced among 5, 9 and 11.

In Figure 8, a significant difference in the energy consumption between the intermediate nodes 5 and 9 can be observed in MRHOF. This gap tends to increase with time and BPD 5 will die sooner impacting the overall network lifetime whereas the energy consumption of the BPDs 5 and 9 are much balanced in the SEEOF algorithm. The lifetime of both nodes are higher in SEEOF than in MRHOF. In summary, SEEOF algorithm balances the energy consumption of the nodes more profitably and extends the network lifetime.

VII. Conclusion and Future Work

In this research, an IPv6 Meshed network for IoT based smart metering with electricity and gas/water meters was designed, allowing the gas/water meters to connect to the network via meshed topology under the standard protocol RPL. A new parent selection algorithm named SEEOF (Smart Energy Efficient Objective Function) was proposed and developed with the goal to utilize the energy consumption efficiently and improve network lifetime. A new cost function was developed for performing parent selection for BPDs that takes into consideration both the link quality and the energy in terms of lifetime. This algorithm was evaluated using COOJA as the simulator and ContikiOS as the operating system, and compared with the existing MRHOF algorithm using the ETX metric. The simulation results show that with this new approach, improvement in the lifetime can be achieved and the energy consumption is balanced among the BPDs in an efficient manner while maintaining the similar packet delivery ratio. The (22% - 27%) improvement in the network life time may not appear to be significant, but balancing energy consumption among the BPD routers in a meshed network is much more significant and is achieved via this new approach.

As for future work, the next step is to perform a real implementation of the proposed algorithm. Secondly, this SEEOF algorithm can be further extended to support a higher number of BPD hops and thereby provide better scalability.

References

[1] "Routing Over Low power and Lossy networks (roll)." [Online]. Available: https://datatracker.ietf.org/wg/roll/charter/.

[2] N. Kushalnagar, G. Montenegro, and C. Schumacher, "IPv6 over low-power wireless personal area networks (6LoWPANs): overview, assumptions, problem statement, and goals," 2007.

[3] "IEEE SA - 802.15.4e-2012 - IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer."

[4] "IEEE SA - 802.15.4g-2012 - IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 3: Physical Layer (PHY) Specifications for Low-Data-Rate, Wireless, Smart Metering Utility Networks."

[5] "M2M Alliance." [Online]. Available: https://m2m-alliance.com/.

[6] "Wi-SUN Alliance." [Online]. Available: https://www.wi-sun.org/index.php/en/.

[7] T. Rault, A. Bouabdallah, and Y. Challal, "Energy efficiency in wireless sensor networks: A top-down survey," Comput. Networks, vol. 67, pp. 104–122, 2014.

[8] T. Winter et al., "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," Internet Eng. Task Force (IETF), Req. Comments 6550, ISSN2070-1721, pp. 1–157, 2012.

[9] "Contiki: The Open Source Operating System for the Internet of Things." [Online]. Available: http://www.contiki-os.org/.

[10] J. Vasseur, M. Kim, K. Pister, N. Dejean, and D. Barthel, "Routing metrics used for path calculation in low-power and lossy networks," RFC 6551, 2012.

[11] P. Thubert, "Objective Function Zero for RPL," RFC 6552, vol. 33, pp. 3–8, 2012.

[12] J. W. Hui, "RFC6553 Option for Carrying RPL Information in Data-plane Diagrams," RFC 6553, vol. 33, pp. 3–8, 2012.

[13] V. Hui, J., Vasseur, J. P., Culler, D., & Manral, "An IPv6 Routing Header for Source Routes with the Routing Protocol for Low-Power and Lossy Networks (RPL)," RFC 6554 Saudi Med J, vol. 33, pp. 3–8, 2012.

[14] O. Gnawali and P. Levis, "The Minimum Rank with Hysteresis Objective Function," IETF RFC 6719, pp. 1–14, 2012.

[15] P. Levis, T. H. Clausen, J. W. Hui, O. Gnawali, and J. Ko, "The Trickle Algorithm," IETF RFC 6206, pp. 1–13, 2011.

[16] H. Ali, "A performance evaluation of rpl in contiki," 2012.

[17] R. Baumann, S. Heimlicher, M. Strasser, and A. Weibel, "A Survey on routing metrics TIK report 262," 2007.

[18] A. A. B. Mohanoor, S. Radhakrishnan, and V. Sarangan, "Online energy aware routing in wireless networks," Ad Hoc Networks, vol. 7, no. 5, pp. 918–931, 2009.

[19] J.-H. Chang and L. Tassiulas, "Energy Conserving Routing in Wireless Ad-hoc Networks," Proc. IEEE INFOCOM 2000, Conf. Comput. Commun. Ninet. Annu. Jt. Conf. IEEE Comput. Commun. Soc. Reach. Promised L. Commun., vol. 1, pp. 22–31, 2000.

[20] D. Kim and J. Garcia-Luna-Aceves, "Routing mechanisms for mobile ad hoc networks based on the energy drain rate," IEEE Trans., 2003.

[21] M. Lotfi, S. Jabbehdari, and M. Shahmirzadi, "A new energy efficient routing algorithm based on a new cost function in wireless ad hoc networks," arXiv Prepr. arXiv1006.4557, 2010.

[22] P. Trakadas and T. Zahariadis, "Design Guidelines for Routing Metrics Composition in LLN," Roll Internet Draft, 2012.

[23] P. Karkazis, P. Trakadas, H. Leligou, and L. Sarakis, "Evaluating routing metric composition approaches for QoS differentiation in low power and lossy networks," Wirel. networks, 2013.

[24] C. Liao, L. Chang, T. Lee, and S. Chen, "An Energy-Efficiency-Oriented Routing Algorithm Over RPL," inf.cyut.edu.tw.

[25] C. Lin, "Composite Metrics for Routing in Low Power and Lossy Networks," inf.cyut.edu.tw.

[26] L. Lassouaoui, S. Rovedakis, F. Sailhan, and A. Wei, "Evaluation of energy aware routing metrics for RPL," in 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2016, pp. 1–8.

[27] A. Dunkels, F. Osterlind, N. Tsiftes, and Z. He, "Software-based on-line energy estimation for sensor nodes," Proc. 4th Work. …, 2007.

[28] P. Trakadas, H. Leligou, T. Zahariadis, and P. Karkazis, Managing QoS for future internet applications over virtual sensor networks. 2013.

[29] S. Ouni and Z. Ayoub, "Predicting communication delay and energy consumption for IEEE 802.15. 4/ZigBee wireless sensor networks," Int. J. Comput. …, 2013.

[30] "TMote Sky DataSheet." [Online]. Available: http://www.eecs.harvard.edu/~konrad/projects/shimmer/references/tmote-sky-datasheet.pdf. [Accessed: 28-Oct-2016].