공학석사 학위논문

An Interference-Tolerant Routing Protocol in RPL-based Multi-hop Networks

RPL기반 다중 홉 네트워크에서 간섭에 강인한 라우팅 프로토콜

2016년 8월

서울대학교 대학원

전기 · 정보 공학부

JINGSHAN CUI

Abstract

Low power and Lossy Networks (LLNs) are made up of many embedded devices. There is a wide scope of application areas for LLNs, including industrial monitoring, healthcare, smart grid AMIs, environmental monitoring, energy management and wireless sensor networks. Wireless sensors run on very constrained devices. So, there are some challenges like Link dynamics, overhead, and complexity.

RPL (Routing Protocol for low power and lossy networks) which is designed to overcome routing issues in LLNs is one of the most successful and widely used protocols.

Nowadays, more and more applications target indoor environment such as office, cafeteria and shopping mall. And several wireless technologies such as Wi-Fi, Bluetooth, Microwave shares the 2.4 GHz ISM band in those environments. Especially Wi-Fi Interference is one of the most critical factors in wireless sensor networks, and it is a new challenge in RPL.

Existing works proposed to improve performance under Wi-Fi interference. But, target of most schemes is link layer. We believe this is the first effort to solve the problem at routing layer.

RPL use ETX (Expected Transmission Count) to indicate link state. If it exceeds ETX-threshold, corresponding parent node will be evicted from parent candidate set. And ETX will be decreased when the node re-added to parent candidate set. But, because of such procedure, ETX value becomes unreliable under Wi-Fi interference.

This research proposes a scheme that could adjust ETX-threshold adaptively. And our results in multi-hop testbed shows that the performance of our scheme is superior to conventional RPL in terms of average end to end PRR, control over head and parent change count.

Keywords: RPL, low power and lossy networks, ETX-threshold, wireless sensor networks, interference

Student number: 2014-22141

Contents

List of Figures

Chapter 1. Introduction

Low−power and lossy networks (LLNs) are typically composed of many embedded devices with limited power, memory, and processing resources [1].

Many approaches have been proposed to run on these nodes and overcome routing issues in LLNs. And one of the most successful and widely used one is RPL (Routing Protocol for Low power and Lossy Networks) which IETF recently standardized [2].

Sensor node shares the 2.4 GHz ISM band with several wireless technologies such as Wi−Fi, Bluetooth, Microwave. So it suffers from cross−technology interference [3]. Wi−Fi is the most critical one [6], and it could be severe if application is under environments like office, cafeteria and shopping mall.

In order for the Wi−Fi and WSN to coexist, several wireless standards incorporate the CSMA as interference mitigation method in the Physical and MAC layer [3]. However, based on the empirical result obtained in a study by Huang et al. [5] the CSMA scheme seems inadequate to fully utilize the Wi−Fi white spaces between the Wi−Fi frames due to the Wi−Fi bursty character. And there are several approaches utilizing channel switching [7], [10], [11], [12], [13]. Such approaches can significantly improve network's performance. But it is often not possible to simply pick a proper channel or there may not be any proper channel at all which is free from interference [4]. Other techniques such as ORW [8] and ORPL

[9], a more recent protocol also uses ORW, mitigate interference by exploiting spatial diversity. But, many duplicate packets are generated, when the network is dense and channel is interfered. And there are many MAC layer solutions proposed [14], [15], [16].

In this paper, we propose an adaptive algorithm to control ETX-threshold in RPL storing mode using OF0 [20] as a routing metric. By doing so, ETX (Expected Transmission Count) value will be more accurate and parent selection will be more appropriate. Proposed mechanism could derive the most appropriate value for the ETX-threshold in order to improve performance under Wi-Fi interference. Then the performance of our proposed scheme is compared against that of the conventional RPL in terms of packet receiption ratio, parent change count, control overhead. We believe this is the first approach that utilizes ETX-threshold to mitigate Wi-Fi interference at routing layer.

The remainder of thesis is organized as follows. Chapter 2 introduces the RPL, Tiny RPL. Chapter 3 describes limitation of RPL. Chapter 4 details the design of proposed scheme. Chapter 5 describes performance evaluation. Final chapter concludes this thesis.

Chapter 2 . Background

In this section, we provide a brief background of RPL. We then describe TinyRPL[19], the default prototype implementation of RPL in the latest TinyOS 2.1.2 as a basis for describing our proposed scheme implementation.

2.1 RPL – IPv6 Routing Protocol for LLN

In order to meet requirements and challenges in LLNs, RPL has been standardized in the IETF ROLL (Routing Over Low-Power and Lossy Networks) Working Group as a suitable routing protocol [17]. RPL is designed to provide efficient routing paths for P2MP (Point-to-Multipoint) and MP2P (Multipoint-to-Point) traffic patterns in LLNs.

RPL is a distance vector routing protocol for LLNs that makes use of IPv6 and it builds a Destination Oriented Directed Acyclic Graph (DODAG) which is routed at a single destination and make sure there is no cycle. DAG is built according to its objective function (OF) and routing information.

In order to construct tree based topology, the RPL mainly utilize two types of control messages: DODAG Information Object (DIO), Destination Advertisement Object (DAO).

DAO enables the construct of downlink path and is used to propagate destination information upwards along the DODAG. And there are some optional control messages we are not going to talk about in this paper.

Upon receiving DIO messages from its neighbors, a node chooses a routing parent according to its OF and local policy, and then constructs a routing topology (i.e., DODAG). DIO is the main source of routing information which are transmitted through the TrickleTimer [21] to achieve a balance between control overhead and fast recovery. It contains information such as node's RANK which is defined and used by the OF to represent the routing distance from a node to the root. Once each node that receives the DIO choose the best parent based on the OF, RPL uses DAO messages for downward route construction, which advertise routing information on how other nodes can reach various destinations and prefixes within an RPL network when traveling down the RPL DODAG. Each node generates a new DAO message whenever it changes its routing parent, and periodically when updates are required. How a DAO message is processed by each node and the LBR depends on whether the network is using RPL's 'storing mode' or 'non-storing mode' for downwards routing [22]. The basic idea is for ancestor nodes to process and store the information in DAO messages to create routing entries for the nodes in the subtree.

2.2 TinyRPL – RPL implementation with OF0

OF0 is designed as a default OF that will allow interoperation between implementations in a wide spectrum of use cases[20]. OF0 does not specify how the link properties are transformed into a RANK and leaves that responsibility to the implementation

TinyRPL is the TinyOS [18] implementation of the RPL with OF0 along with hop count and ETX metrics. It provides all the basic features of the RPL except for some optional functionality. TinyRPL uses RANK and ETX for parent selection. RANK indicates hop count and RANK of root is always 1. Node broadcasts DIO messages containing RANK. ETX is a link quality indicator between child node and its parent candidate. For example, child node can measure ETX from itself to parent by dividing the number of total transmissions from itself to parent by the number of successful transmissions from itself to parent. So, high ETX means bad link quality.

RPL updates ETX using an exponentially weighted moving average (EWMA) filter, making it robust to sudden changes in link condition.

Each node recognizes its neighbor nodes by DIO messages received from them. Each node k except root generates its parent candidate set P_k from its neighbor set N_k as

$$P_k = \{n_k \in N_k \mid h(n_k) < h_k, ETX(k, n_k < TH_{ETX})\} \qquad (1)$$

TH_{ETX} is a threshold to remove neighbors which are connected through unreliable links. h(k) is the hop count between node k and the root. Each node performs parent candidate set management and parent selection when receives DIO with changed information.

Parent candidate set management contains three operations as follow

- Add: When child node receives DIO from a totally new node, child node will add this node to parent candidate set. But, if a node does not have any parent node, any node could be added to parent candidate set by sending DIO.
- Evict: If a parent candidate node' s RANK is not smaller than child node' s RANK or corresponding link ETX is bigger than ETX−threshold, child node will evict this node from parent candidate set.
- Re−add: When child node receives DIO from an evicted node, child node will re−add this node to parent candidate set. And corresponding link ETX will be decreased.

Thus, RPL allows each node to keep ETX for all nodes in parent candidate set which is smaller than ETX−threshold.

A child node selects its best parent node as a preferred parent node according to routing metric given as

$$R(p_k) = \mathrm{RANK}(p_k) + \mathrm{ETX}(k, p_k) \qquad (2)$$

Then, it change its parent node from the current parent p_k to another node $\hat{p}_k$ if

$$R(\hat{p}_k) < R(p_k) - c \quad (3)$$

Where c is a stability bound to mitigate unnecessary and inefficient parent changes, which is set to 0.5 by default. This is a hysteresis component of TinyRPL, and we refer to Eq. (3) as the stability condition.

Chapter 3 . Limitations of RPL with constant ETX−threshold

In this section, we first provide an experimental measurement study of RPL with constant ETX−threshold for all nodes on a real multihop LLN testbed. Observations presented in this section will provide the motivation for proposed scheme, a distributed ETX−threshold control mechanism which enables adaptive ETX−threshold among nodes.

3.1 Effect of Wi−Fi interference

Through experiments, we evaluated various performance metrics of RPL with or without Wi−Fi interference. Sensor nodes use transmission power −10dBm and generate 2 uplink packets per minute on 802.15.4 channel 14. Wi−Fi AP uses transmission power 16dBm and generates various downlink traffic on 802.11 channel 2.

We find out that average end−to−end packet reception ratio (PRR) is nearly perfect when there is no Wi−Fi interference, which means that RPL establishes a reliable routing topology with reasonable link connectivity in our testbed environment. However, PRR decreases significantly with Wi−Fi interference and some nodes experience end to end PRR as low as 10%.

Most packet losses occur due to link congestion. And we observe that average one−hop ETX is increasing under interference. This indicates that link layers are experiencing more packet losses and retransmissions under Wi–Fi interference in overlapping channel.

Furthermore, we analyzed parent change, control overhead and parent candidate set management. We find out that event like evict and re–add, control overhead and parent change count increases significantly under Wi–Fi interference.

RPL changes parent nodes frequently under interference. This is because each node tries to avoid bad link by selecting an alternative link, and ETX which indicate quality of link plays a dominant role. Furthermore, control overhead also increases significantly under interference. Parent change causes DAO message generation in order to set up downlink route. And nodes will generate extra DIO message since it resets TrickleTimer when it detects routing inconsistency.

Above discussion reveals that RPL's inefficient operation under Wi–Fi interference causes extra overhead and average packet reception ratio.

3.2 Effect of ETX–threshold

Based on the above performance evaluations, we analyzed reason that cause performance degradation and found out a constant parameter named ETX–threshold affects performance significantly by conducting additional experiments with various ETX–threshold under Wi–Fi interference.

Link ETX will be increased when it affected by Wi-Fi interference. Once the ETX exceeds ETX-threshold, node will evict corresponding parent node from parent candidate set, then, change parent. Latter, the evicted link's ETX will be decreased when the child node re-add the evicted node to parent candidate set by receiving DIO message. If there's no ETX reduction procedure, corresponding node will not be selected as parent node again after ETX exceed ETX-threshold.

If ETX-threshold is set to low value, ETX of a link that affected by interference will easily exceed ETX-threshold and evicted. Then, ETX will be reduced to a value smaller than ETX-threshold when it re-added to parent candidate set. But actual link ETX should be greater than ETX-threshold due to severe interference, so the link will frequently repeat this inefficient procedure and ETX of affected link is inaccurate. In other word, child node could not keep high ETX value accurately for bad links. Figure 1 shows an example of this problem. ETX-threshold is set to 4. Due to high power Wi-Fi AP, all three links are affected by interference. ETX in black color indicates actual link state, and ETX in red color indicates value saved by child node A. as figure shows, all ETX values saved by node A are smaller than ETX-threshold. Once ETX exceeds ETX-threshold, link will be evicted and child node will change parent node. But in this example, all links will easily exceed threshold again. So it causes unnecessary frequent parent change.

Figure 2 shows another problem. ETX-threshold is also set to 4. Node B is relatively far from node A which has lower Rank and bad link because of interference and distance. Node B's DIO messages does not always reach to node A. So, before node A receives DIO from node B, node A's parent candidate set may contains node D, E and F. In this example, if node A select node F as parent node according to OF, node A's Rank will become to 4. Then, after node A receives the first DIO message from node B, node A will add node B to its parent candidate set and conduct parent node selection. Obviously, node B is the best one according to OF, because initial ETX is 1. Then, node B will become parent of node A and node A's Rank become to 3. Node D, E and F will be evicted from parent candidate set, because rank of node A is not bigger than rank of node D, E and F. But link of node B is bad due to interference and distance, ETX will exceed ETX-threshold easily. After eviction of node B, node A has no parent. Then, after some control messages exchanged, node D, E and F could be re-added to parent candidate set. If node B's DIO received by node A at this point, node A has high probability to select node B as parent again, because ETX value should always smaller than ETX-threshold even if link ETX of node B is far bigger than that.

Furthermore, problem case 2 could cause chained problem. After node A become no parent state, node A will broadcast infinite RANK by sending DIO message. So, this could cause problem that similar to problem case 2 to node A's child node.

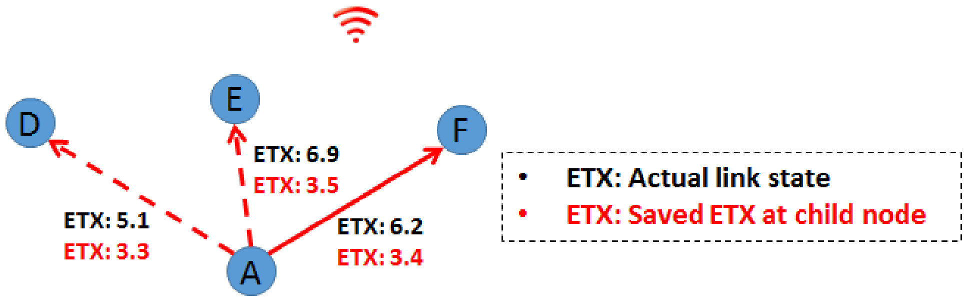

Fig.1 problem case 1 of RPL when ETX-threshold is small

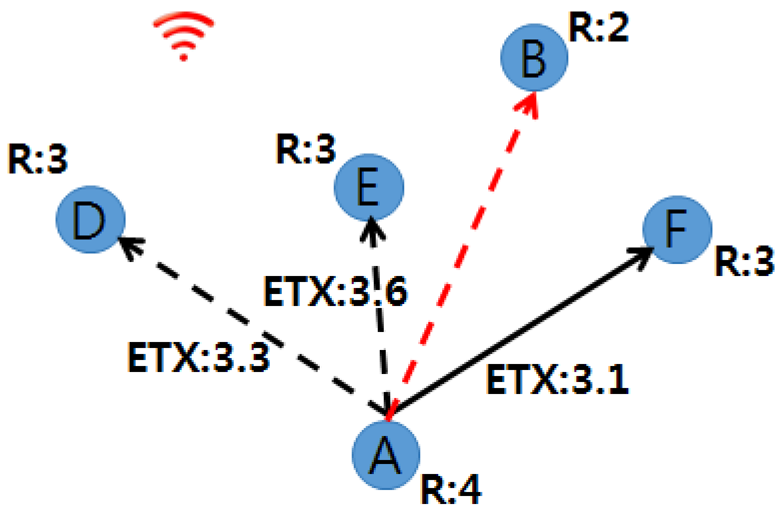

Fig.2 problem case 2 of RPL when ETX-threshold is small

If ETX−threshold is set to high value, another problem as figure 3 shows could be happen. ETX−threshold is set to 8. Node E is selected as parent node by node A, D and F. Rank of node E is 2. This means Rank of node A, D and F equal to 3. This also means node D and F could not exist in parent candidate set of node A until node E evicted from node A’ s parent candidate set. But ETX−threshold is much higher than red link’ s ETX, so, node A will hold bad link for long time even there are better options.

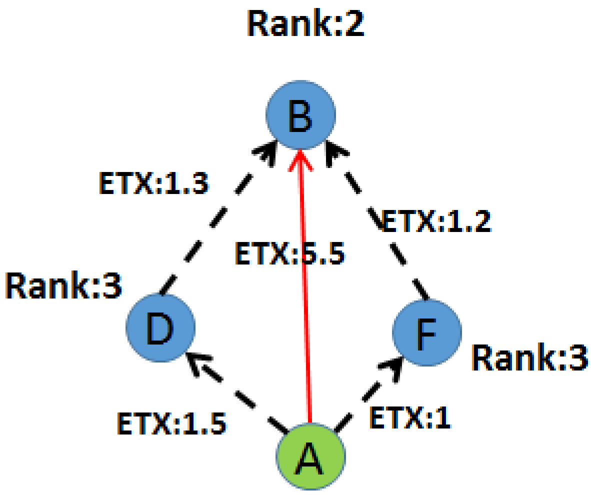

Fig.3 problem case of RPL when ETX-threshold is large

3.3 Summary

Based on above findings, our summary is as follows:

- Low ETX−Threshold: give up bad links fast, and try another link fast. But, events like Evict and Re−add happen frequently under Wi−Fi interference. This causes inaccurate ETX value and frequent parent change because ETX could not exceed ETX−threshold. Additionally, parent change could be meaningless due to inaccurate ETX.
- High ETX−Threshold: nodes could maintain accurate ETX for bad links. So child nodes could select proper parent according to objective function. But, even if there is a better link, child node may persist in current parent with bad link.

These pros and cons indicate that trade off exists. This motivates us to design a scheme that control ETX−threshold adaptively in order to work properly under Wi-Fi interference.

Chapter 4. Proposed scheme design

Problems of conventional RPL are described in section 3. RPL with constant ETX−threshold does not work properly. In this section, we describe proposed scheme in detail. Proposed scheme is designed to achieve reliable performance under Wi−Fi interference through adaptive and distributed ETX−threshold control. In brief, proposed scheme provides a new mechanism which manages independent ETX−threshold for each neighbor nodes. Specifically, proposal has two types of threshold, one is ETX−threshold which works as upper bound, and another one works as lower bound. When ETX of a link exceeds upper bound due to interference or obstacle, child node will increase ETX−threshold of corresponding neighbor node. On the contrary, if ETX reduces to a value smaller than lower bound, child node will decrease ETX−threshold. Proposed scheme adaptively control these thresholds to stabilize routing without sacrificing reliability especially under interference. Additionally, proposed scheme improves end to end packet reception ratio and reduces control overhead.

4.1 ETX−threshold control

Compared to the standard RPL, the most distinct feature of proposed scheme is that it uses ETX−threshold as a variable and adjust the parameter according to link ETX. Initial ETX of a newly added link is set to 1 which indicates the best condition. If the link between child and parent node becomes bad and exceeds ETX−threshold, ETX−threshold of the link will be increased according to following equation.

$$(\mathrm{f} \cdot \mathrm{f} \cdots \mathrm{f})(\mathrm{ETX}') = \mathrm{f}(\mathrm{f}(\mathrm{f}(\cdots \mathrm{f}(\mathrm{ETX}') = f^n(ETX') \qquad (4)$$

$\mathrm{f(ETX)}$ is defined as follow

$$\mathrm{f(ETX)} = 0.8 \times \mathrm{ETX} + 0.2 \times \mathrm{ReTX\_MAX} \qquad (5)$$

ETX′ indicates ETX value when it exceeds threshold. ReTX_MAX in equation indicates maximum retransmission count. Actually, if we replace ReTX_MAX with retransmission count, the equation will describes how RPL updates ETX after each transmission. So, $\mathrm{f(ETX)}$ means ETX value when considering one link loss, and f^nmeans ETX value when considering n consecutive link losses.

Additionally, standard RPL reduces ETX of a re−added link, this is why child node repeat evict and re−add frequently under Wi−Fi interference. In proposed scheme, we do not decrease ETX when re−add a link, because child node will increase ETX−threshold of evicted links. By doing this, child node could maintain accurate ETX for each link and routing decisions will be more accurate, which minimizes meaningless parent changes and control overheads.

4.2 Lower bound control

Proposed scheme not only provides increasing part but also provides decreasing part. When ETX exceeds ETX−threshold, we get ETX´, and lower bound is simply ETX´ minus BETA. ETX will fluctuate even if link is stable. BETA works as stability bound, which prevent ETX−threshold from decreasing immediately after increase. When ETX become smaller than lower bound we consider it as a new ETX´ and get new decreased ETX−threshold according to equation (4). By doing so, gap between ETX and ETX−threshold could be constrained to some degree, and prevent improper routing described in figure 3 happen.

In this way, child nodes could manage independent ETX−threshold for each neighbor node. So, child node could make better routing decision to achieve better performance.

Chapter 5. Performance evaluation

This section verifies the performance of our proposed scheme. Performance of proposed scheme is compared against conventional RPL through experimental measurements on office environment testbed.

5.1 Experimental Setup

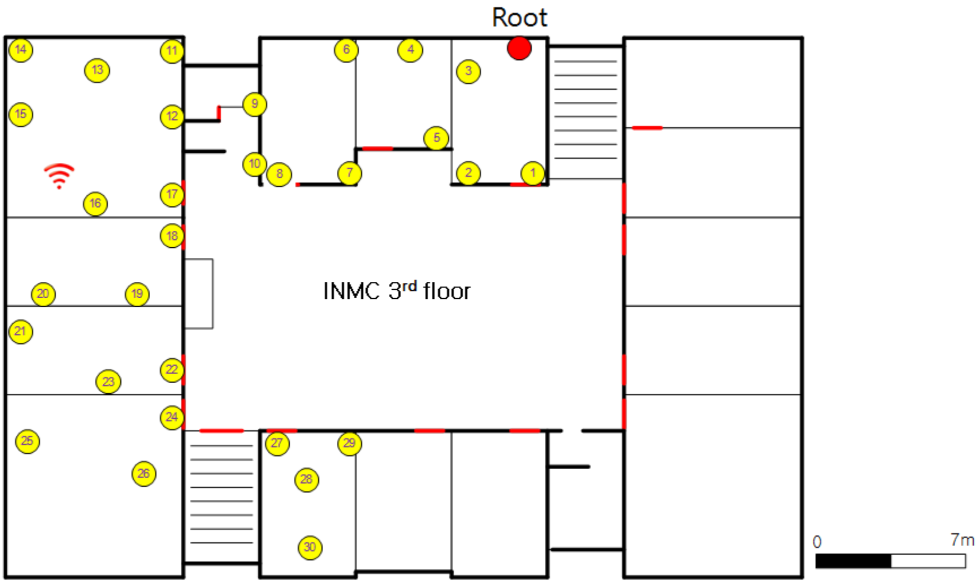

Fig.4 Testbed map

As shown in figure 4, we deploy a network testbed in the office building. There are 30 LLN endpoints and one root node. Each LLN node is a TelosB clone device[23] with an MSP430 microcontroller, a CC2420 radio and 5dB gain antenna.

All of the experiments are conducted over the channel 14 of IEEE

802.15.4 link and transmission power is set to −10dBm. All the nodes save its energy through the low power listening based duty cycling, except root node. Sleep interval is set to 0.5 seconds, and all the sensor nodes generate uplink data packet with traffic rate of 2 packets per minute. Maximum retransmission is set to 10, which means maximum ETX is 10.

We artificially add interference During experiments. Wi−Fi AP generates 30Mbps downlink traffic in average over channel 2 of IEEE 802.11. AP's power is set to 16dBm. Furthermore, in order to minimize unexpected Wi−Fi interference, experiments are conducted at dawn.

5.2 Experimental Result

Two experimental scenarios are designed. In scenario 1 we verify the effect of proposed scheme against conventional RPL under Wi−Fi interference. ETX−threshold of conventional RPL is set to 2,4,6,8 and 10 respectively. Each experiment conducted for 60 minutes. Figure 5 shows the result of average end to end packet reception ratio, and it plotted into box plot. The upper edge of the box means the third quartile and the lower edge of the box means the first quartile. A horizontal line near the middle of the rectangle indicates the median. A vertical line extends from the top of the rectangle to indicate the maximum value, and another vertical line extends from the bottom of the rectangle to indicate the minimum value. Surprisingly high maximums or surprisingly low minimums in figures called outliers.

As figure 5 shows, RPL with threshold 6 show the best performance among RPL with constant ETX-threshold, and proposed scheme performs better than that. RPL with threshold 2 shows the worst performance, because too many unnecessary evictions, parent changes happen. RPL with threshold 10 shows relatively lower performance than RPL with fixed ETX-threshold 8. This is because ETX of a link could not exceed 10, in another word, node will never evict a parent even if the link become unavailable.

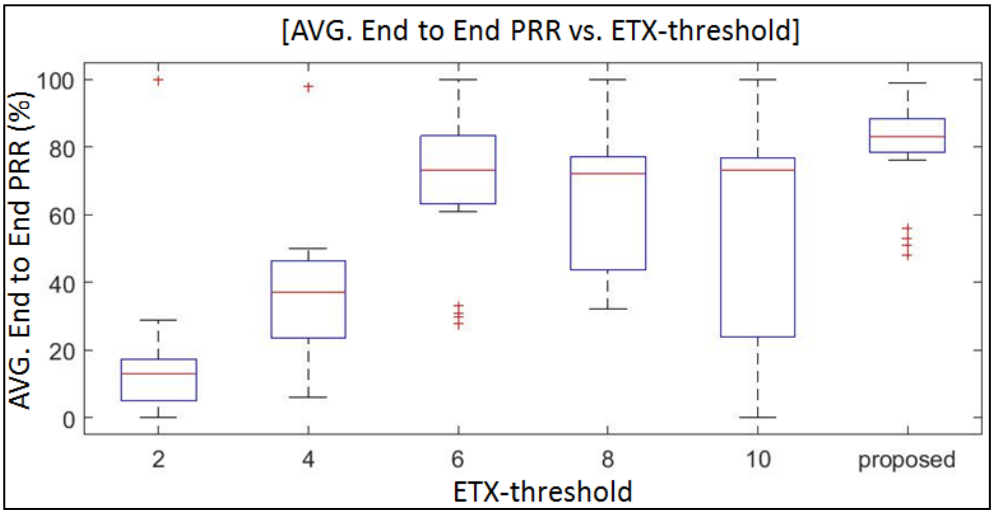

Fig.5 Average End to End PRR in scenario 1

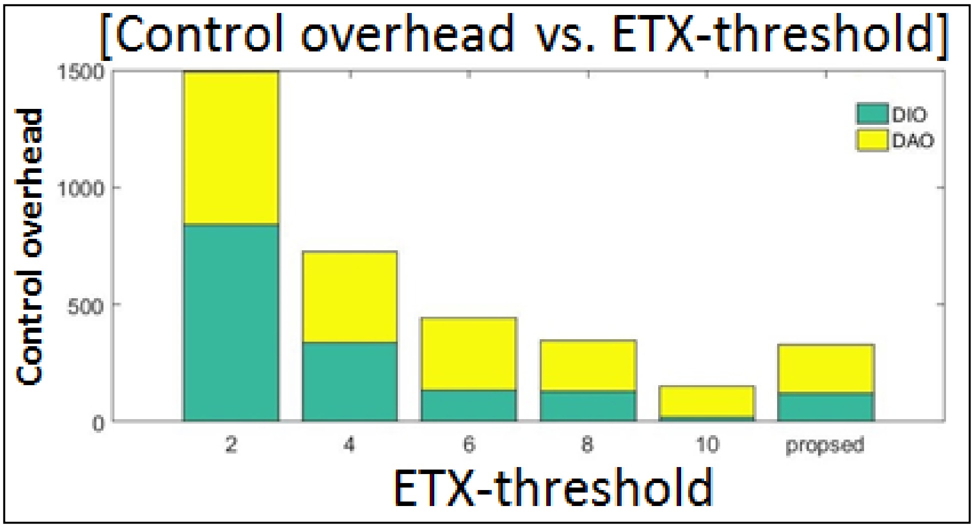

Fig. 6 Control over head in scenario 1

All scheme uses the same Trickle algorithm and it resets the control packet transmission interval to the shortest value when the route inconsistency is detected like the parent change, eviction. Figure 6 shows result of control overhead. Obviously, RPL with threshold 2 generates the largest number of control packets. RPL with threshold 10 shows the best performance in control overhead, but, it does not mean good performance, because node will never evict parent node even the link is unavailable.

Figure 7 shows parent change count. As described in control overhead part, RPL with ETX−threshold 2 shows the worst performance due to same reason. So is RPL with constant ETX−threshold 10.

Figure 8 shows average one hop ETX for each scheme. We measured this one hop ETX for each node by dividing the number of total transmissions it made by the number of successful transmissions it made. Then, we took average. Obviously, RPL with fixed ETX−threshold value 10 shows the worst performance. Proposed one shows the best performance.

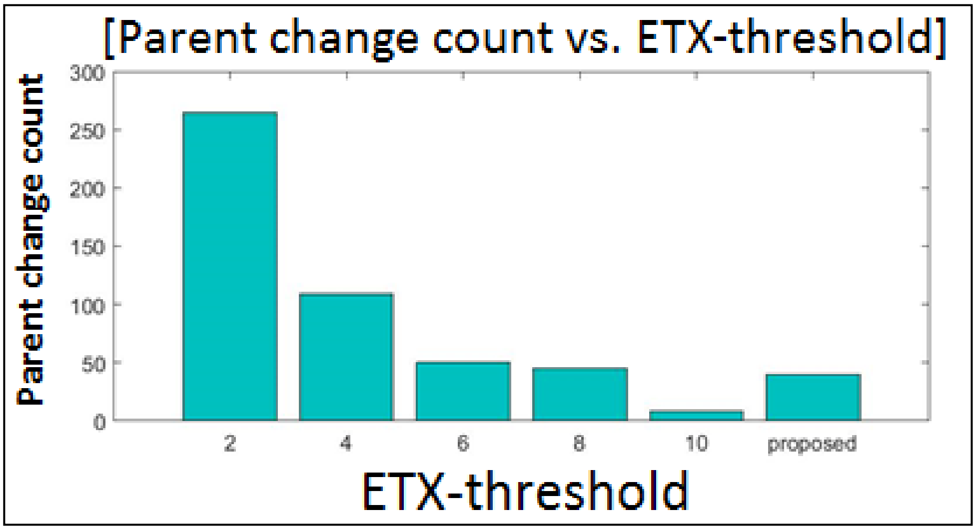

Fig.7 Parent change count in scenario 1

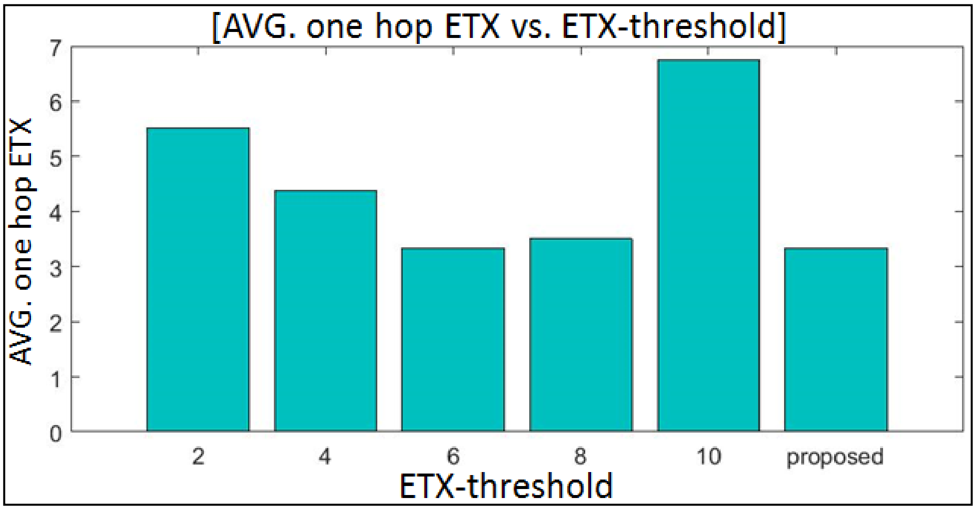

Fig.8 Average one hop ETX in scenario 1

In scenario 2, we did similar experiments to scenario 1 to verify the effect of proposed scheme against conventional RPL. Each experiment conducted for 60 minutes. Only difference is Wi−Fi interference is added at the first and the last 20 minutes.

Proposed scheme in scenario 2 also shows the best performance as figure 9 shows.

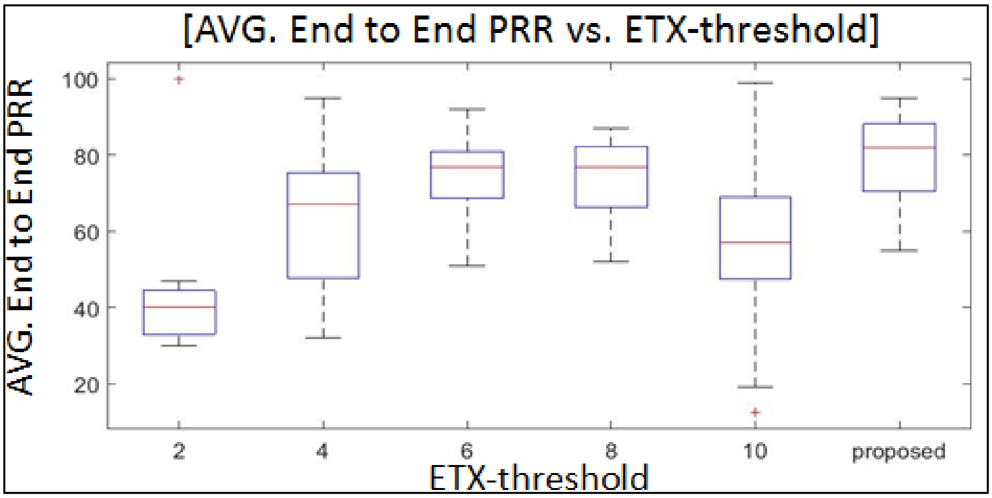

Fig.9 Average End to End PRR in scenario 2

Figure 10 shows average end to end PRR in first, second and the last 20 minutes respectively. Shaded parts indicate existence of interference. We could see that proposed scheme shows almost perfect performance without Wi-Fi interference, and similar result under Wi-Fi interference when compare with scenario 1.

Figure 11 shows ETX-threshold management in scenario 2 at node number 25, and colors on the x axis indicate current parent. P.C. is abbreviation of parent candidate. We could see that our scheme works well.

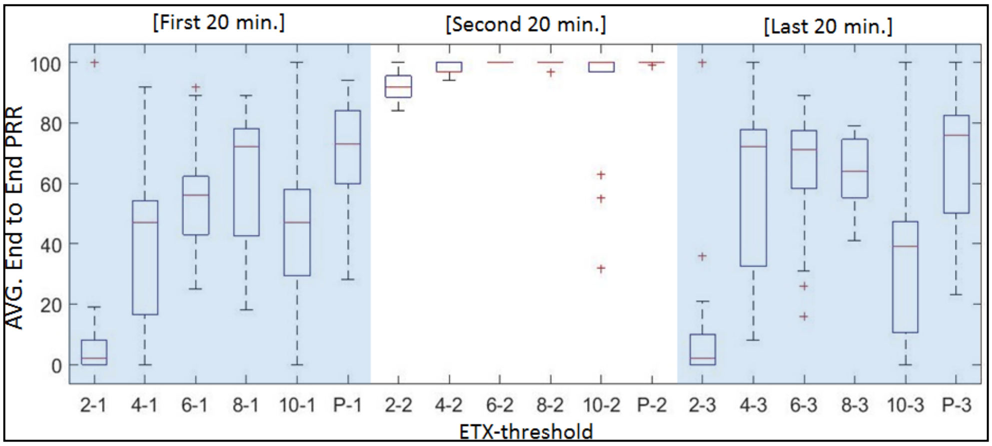

Fig.10 Average End to End PRR in each 20minutes

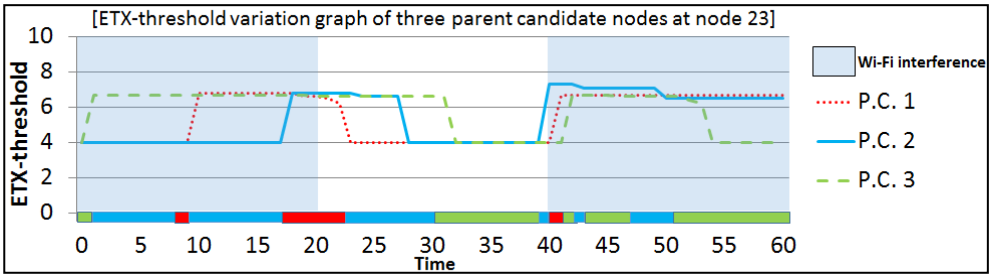

Fig.11 ETX−thresholds of nodes in parent candidate set at node number 25

Chapter 6. Conclusion

We confirmed that default RPL does not work well under Wi-Fi interference. Via analysis of reason to the problem and additional experiments, we find out that adjust ETX-threshold could make significant performance improvement at some environments. Then we confirmed there is trade-off.

We propose an Interference-Tolerant Routing Protocol in RPL-based Multi-hop Networks which adjust ETX-threshold adaptively to improve reliability under severe interference, which characterizes an office environment. Through several experiments in testbed with 31 nodes and two different settings, we show the significant performance gain in comparison to the conventional RPL.

References

[1] A. Brandt, J. Buron, and G. Porcu. Home Automation Routing Requirements in Low-Power and Lossy Networks. RFC 5826, Apr. 2010.

[2] Hui, Jonathan, and J. Vasseur. "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks." Internet Requests for Comment, RFC Editor, Fremont, CA, USA, Tech. Rep 6550 (2012).

[3] Azmi, N., et al. "Interference issues and mitigation method in WSN 2.4 GHz ISM band: A survey." Electronic Design (ICED), 2014 2nd International Conference on. IEEE, 2014.

[4] Mohammad, Mobashir, XiangFa Guo, and Mun Choon Chan. "Oppcast: Exploiting spatial and channel diversity for robust data collection in urban environments." 2016 15th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN). IEEE, 2016.

[5] S. Zacharias and T. Neve, "Technologies and architectures for multimedia-support in wireless sensor networks," Smart Wirel. Sens. Networks, InTech, pp. 373–394, 2010.

[6] A. Sikora and V. F. Groza, "Coexistence of IEEE802. 15.4 with other systems in the 2.4 GHz-ISM-Band," in IEEE Instrumentation and Measurement Technology Conference (IMTC), 2005, vol. 3, pp. 1786– 1791.

[7] J. Yun, B. Lee, J. Li, and K. Han, "A channel switching scheme for avoiding interference of between IEEE 802.15.4 and other

networks," Int. Multi−symposium Comput. Comput. Sci., pp. 136–139, 2008.
[8] O. Landsiedel, E. Ghadimi, S. Duquennoy, and M. Johansson. Low power, low delay: opportunistic routing meets duty cycling. In IPSN. IEEE, 2012.
[9] S. Duquennoy, O. Landsiedel, and T. Voigt. Let the tree bloom: scalable opportunistic routing with orpl. In SenSys. ACM, 2013.
[10] M. Doddavenkatappa, M. C. Chan, and B. Leong. Splash: Fast data dissemination with constructive interference in wireless sensor networks. In NSDI. USENIX, 2013.
[11] V. Iyer, M. Woehrle, and K. Langendoen. Chrysso: A multi−channel approach to mitigate external interference. In SECON. IEEE, 2011.
[12] Y. Wu, J. Stankovic, T. He, S. Lin, et al. Realistic and efficient multichannel communications in wireless sensor networks. In INFOCOM. IEEE, 2008.
[13] T. Watteyne, A. Mehta, and K. Pister. Reliability through frequency diversity: why channel hopping makes sense. In PE−WASUN. ACM, 2009.
[14] O. D. Incel, L. van Hoesel, P. Jansen, and P. Havinga. Mc−lmac: A multichannel mac protocol for wireless sensor networks. Ad Hoc Networks, 9(1):73–94, 2011.
[15] Y. Kim, H. Shin, and H. Cha. Y−mac: An energy−efficient multi−channel mac protocol for dense wireless sensor networks. In IPSN. IEEE, 2008.
[16] H. K. Le, D. Henriksson, and T. Abdelzaher. A practical multi−

channel media access control protocol for wireless sensor networks. In IPSN. IEEE, 2008.

[17] Hui, Jonathan, and J. Vasseur. "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks." Internet Requests for Comment, RFC Editor, Fremont, CA, USA, Tech. Rep 6550 (2012).

[18] David Gay, David Culler, and Philip Levis. TinyOS/nesC Programming Reference Manual. Available at: http://www.tinyos.net/dist-2.0.0/tinyos-2.0.0beta1/doc/nesc/ref.pdf,2002.

[19] JeongGil Ko, Joakim Eriksson, Nicolas Tsiftes, Stephen Dawson-Haggerty, Andreas Terzis, Adam Dunkels, and David Culler. ContikiRPL and TinyRPL: Happy Together. In Proceedings of the workshop on Extending the Internet to Low power and Lossy Networks (IP+SN 2011), Chicago, USA, April 2011.

[20] Thubert, P., Ed., "Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)", RFC 6552, March 2012.

[21] P. Levis, N. Patel, D. Culler, and S. Shenker. Trickle: A Self-regulating Algorithm for Code Propagation and Maintenance in Wireless Sensor Networks. In Proceedings of the USENIX/ACM Symposium on Networked Systems Design and Implementation (NSDI'04), 2004.

[22] J. Ko, J. Jeong, J. Park, J. A. Jun, O. Gnawali, and J. Paek. DualMOPRPL: Supporting Multiple Modes of Downward Routing in a Single RPL Network. ACM Transactions on Sensor Networks, 11(2):39:1–39:20, Mar. 2015.

[23] J. Polastre, R. Szewczyk, and D. Culler, “Telos: Enabling Ultra−Low Power Wireless Research,” in Proceedings of IPSN/SPOTS, 2005.

초 록

서울대학교 대학원

전기 · 정보 공학부

JINGSHAN CUI

저전력 손실 네트워크의 응용분야는 smart grid, AMI, 환경 모니터링, 센서 네트워크 등 종류가 다양하다. 센서 네트워크는 데이터를 수집하는 극히 제한적인 장치로 구성되었다. 인터넷의 원활한 사용을 위한 인터넷 표준규격을 개발하고 있는 조사위원회인 IETF가 저전력 손실 네트워크에서의 라우팅을 극복하기 위해서 RPL (IPv6 Routing Protocol for Low power and Lossy Networks)이라는 네트워크 프로토콜을 표준화하였다.

센서 노드는 여러 가지 무선 기술인 와이파이 블루투스 등과 함께 2.4기가 대역의 ISM 밴드를 공유하고 있는데 최근 점점 많은 어플리케이션이 나타나면서 오피스, 쇼핑몰과 같은 환경에서는 와이파이 간섭이라는 문제점도 극복해야 된다.

이런 문제를 해결하기 위해서 많은 기법이 제안 되었지만 대부분 링크 레이어를 타겟팅 했고 RPL을 위한 라우팅 레이어에서의 기법은 없는 걸로 알고 있다.

RPL은 상향 링크 트래픽으로 추정한 ETX (Expected Transmission Count)를 사용하여 상향 링크 경로를 설정하며, 추정한 ETX가 ETX-threshold라는 상한 값을 초과할 시 링크를 부모 리스트로부터 제거한다. 이후 부모 리스트에 해당 링크가 다시 추가될 때 ETX 값을 감소해

서 업데이트 한다. 그러나 이러한 동작으로 인해 링크는 정확한 ETX값을 유지하지 못하게 된다. 본 논문에서는 이러한 문제를 해결하기 위해 채널 상태에 따라 ETX-threshold를 적응적으로 조절하는 기법을 제안한다. 최종적으로 다중 홉 테스트베드 상에서의 실험을 통해 제안 기법 성능을 확인한다

Keywords : RPL, low power and lossy networks, ETX-threshold, wireless sensor networks

Student Number : 2014-22141