M. S. Thesis

Transmission Power Control for Large Scale Industrial Applications in Low Power and Lossy Networks

저전력 손실 네트워크에서 대규모 응용분야를 위한 전송전력 제어기법

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지도교수 박 세 웅

이 논문을 공학석사 학위논문으로 제출함

2015 년 8 월

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전기정보 공학부

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Abstract

Transmission Power Control for Large Scale Industrial Applications in Low Power and Lossy Networks

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Transmission power is an important factor which impacts on routing topology in low power and lossy networks (LLNs). LLNs have been designed for low rate traffic where use of maximum transmission power is the best choice for performance maximization since it results in reduced hop distance and transmission overhead. However, large scale applications also require LLNs to deliver very high rate traffic. In such large scale applications, the nodes which are near the root node will incur heavy traffic even though each node generates low rate traffic. As a result, it will cause severe link congestion. In this paper, we first investigate the effect of transmission power control on the performance of the routing protocol for LLNs (RPL) at heavy traffic load through testbed experiments. Our experiments show that, unlike LLNs in low rate applications, packet delivery performance at heavy load first increases and then decreases with transmission power. And we further investigate the reasons of what makes packet loss rate have a convex curve according to transmission power by per node analysis. We classify packet losses into link loss and queue loss. From the experiment results, we observe that link and queue losses are significantly unbalanced among nodes, which causes the load balancing problem of RPL. Furthermore, queue losses occur at the nodes which experience severe link loss. To solve this problem, we propose a simple power control mechanism, which allows each node to adaptively control its transmission power according to its own link and queue losses. Our proposal significantly improves the packet delivery performance by balancing the traffic load within a routing tree. We show performance improvement through experimental measurements on a real mutihop LLN testbed running RPL over IEEE 802.15.4.

Keywords: RPL, low power and lossy networks, transmission power, reliability, load balancing, wireless sensor networks

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Chapter 1 Introduction

The power of wireless sensor networks is an important factor, because most of their devices are under the constrained energy supply [1] [3] [11] [13] [16] [18] [19]. Traditionally, low power and lossy networks (LLNs) have considered low rate traffic where the use of maximum transmission power can maximize performance by minimizing relay burden and hop distance. Under a constrained energy supply, transmission efficiency and network reliability are at variance with each other. Network reliability can be improved by using maximum transmission power [26], whereas this circumstance leads to unnecessarily high energy consumption, which is the main reason for inefficiency. It is quite challenging to use lower transmission power that meets the required specified network reliability while guaranteeing transmission efficiency.

IPv6 routing protocol for low power and lossy networks (RPL) is one of the most common protocol that fits the various requirements required by LLNs [27] [28]. To control transmission power dynamically, RPL uses CC2420 as radio hardware, which can specify the transmission power while running in LLNs [31]. Since standard RPL considers only hop distance and link quality for parent selection, not take node density or network congestion into account, it cannot satisfy large scale industrial applications such as upcoming Smart Grid service [13] [39], which incur heavy traffic near the root node even though each node generates low rate traffic.

There are lots of power control researches on LLNs [4] [7] [10] [11] [12] [16] – [19]. Many transmission power control mechanisms in LLNs use a single transmission power for the whole network, rather than making full use of configurable transmission power provided by CC2420. The authors in [6] [7] [11] proposed a new routing metric which combines expected lifetime with ETX and rank to balance the consumed energy between the nodes for maximizing the network lifetime. These methods are focus on energy saving, which do not exactly appropriate for the different requirements of wireless sensor networks. Some other researches take the configurable transmission powers into consideration in LLNs. For example, ATPC [3] uses RSSI values which are reported by the receiver to adjust transmission power to save power consumption, while guaranteeing link quality within desired range. TPCB [5] proposes a packet-based transmission power control mechanism to optimize performance. These dynamic power control mechanisms adaptively adjust each node's transmission power to save energy. However, all of them do not consider power control in an RPL-based LLN. Our research question is like below: Is the use of maximum and equal transmission power for all nodes still the best choice for heavy traffic delivery in RPL-based LLNs?

In this paper, we try to solve the load balancing and congestion problem of RPL by transmission power control, which allows each node to adaptively control its transmission power according to its own congestion condition. The experimental results indicate that proposed method significantly improves packet delivery performance. We show performance improvements of transmission power control mechanism through experimental measurements on a real multihop LLN testbed running RPL over IEEE 802.15.4. To the best of our knowledge, this is the first experimental study which considers the impact of transmission power control on RPL-based LLNs.

The remainder of the paper is organized as follows. Chapter 2 introduces the experimental environments and chapter 3 describes the load balancing problem of RPL by showing the pre-research experimental results. Chapter 4 proposes power control mechanism and chapter 5 gives the performance comparison between default RPL and proposed method. Finally, chapter 6 concludes this paper and gives some future research directions.

Chapter 2 Experimental Environments

Before introduce experimental environments, the routing protocol should be addressed. In LLNs environment, it is quite important to provide the routing maintenance using the lowest costs [11]. The IPv6 routing protocol for low power and lossy networks (RPL), which is defined in IETF RFC 6550 [2], is one of the traditional wireless sensor network routing protocols. It provides an effective routing mechanism in the IPv6 low power wireless personal area network.

2.1. IPv6 routing protocol for low power and lossy networks (RPL)

RPL is shorted for the IPv6 Routing Protocol for Low power and Lossy Networks, which is made by Routing Over Low power and Lossy networks (ROLL). And RPL is a distance vector based routing protocol that builds directed acyclic graphs (DAGs) according to specific routing metrics, like hop distance, ETX, or energy. Hop distance denotes as the virtual distance of each node to the root and the ETX of a link indicates the predicted number of transmissions which is required to deliver a packet successfully.

RPL constructs tree-like topology where all the nodes send data packets to a single destination, where tree-like topology is called destination oriented directed acyclic graph (DODAG) and the destination is defined as DODAG root or shorted as root. The root acts as a border router for the DODAG. RPL defines optimization objective when forming paths towards roots based on the specified metrics. Default metrics may include rank, and ETX in RPL. Rank defines a node's relative position within a DODAG with respect to the DODAG root, which means hop count from the DODAG root. ETX indicates expected transmission count, which is a fairly common routing metric. When a node selects the parent, it will choose the node which has the lowest rank and ETX value. However, many researches also include power or energy into metric. There are three kinds of control messages, DODAG Information Object (DIO), Destination Advertisement Object (DAO) and DODAG Information Solicitation (DIS). DIO message is similar to hello message, through DIO message, RPL establish upward routes from leaf nodes towards DODAG roots. Each node periodically broadcasts DIO message to maintain the DODAG. DIO messages carries necessary information, including node rank, objective function, etc. On the other hand, RPL employs DAO messages to propagate destination information upward along the DODAG to establish downward routes. DIS messages will be used to solicit a DIO from a RPL node. However, standard RPL considers only hop distance and link quality for parent selection. Therefore, RPL suffers from load balancing problem in practice.

2.2. Experimental environments

We deploy a network testbed in the office building as depicted in Fig. 1. There are 30 LLN sensor nodes and one root node which is marked with the red star. Each node is a telosB cloned device which employs CSMA and a FIFO transmit queue size of 10 packets. We make all the sensor nodes generate data packet to the root node with traffic rate of 40 packets per minute (ppm). This incurs traffic load of 1200 ppm for the root node. And every node also delivers data packets, which are from the children nodes, to root node.

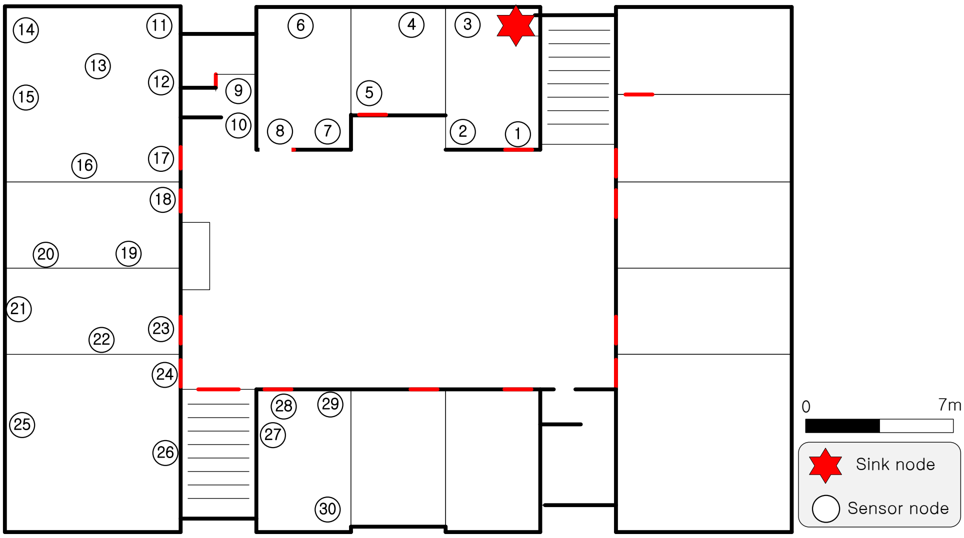

Fig. 1. Test-bed topology map.

Each node uses CC2420 radio, and their transmission power range is from minus 15dBm to 0dBm. We make all nodes use the same transmission power to send DIO message or deliver data packet at the experiments. In order to use the stable link, we only do the experiments at night time. Because there are too much interferences in day time. The protocol stack is like this. In routing layer, we use RPL protocol, in MAC layer, we use CSMA, and in physical layer, we use IEEE 802.15.4. The major parameter settings are summarized in Table 1.

Table. 1. Parameter Settings in Standard RPL

Number of sensor nodes	30
Transmission power	-15 ~ 0 dBm
Traffic load	40 packets/min/node
Queue size	10 packets

Chapter 3 Load Balancing Problem of RPL

In this chapter, we show the experimental measurement study of RPL within high traffic condition. In such high traffic condition, our experimental results shows that packet delivery performance does not always be better when increasing the transmission power. We find that most of packet losses are due to congestion, especially happen to the node which has many children.

3.1. Packet loss rate

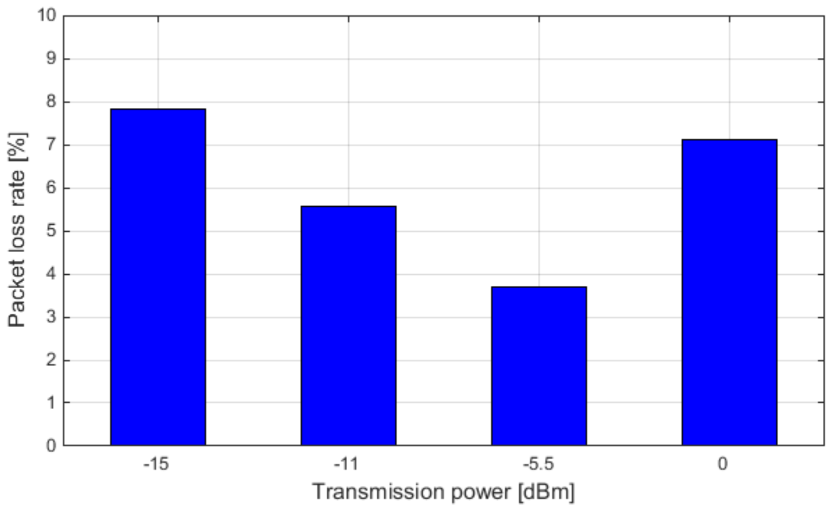

Fig. 2. Tx. power vs. Packet loss rate.

Fig. 2 shows the average packet loss rate of all 30 nodes with varying transmission power. Packet loss rate is used to quantify how reliably a protocol can deliver packets to the destination. The experimental results indicate packet loss rate first decreases but increases again while increasing transmission power. We can see that use of too small transmission power (e.g., -15dBm) decreases network reliability. Interestingly, use of maximum transmission power (i.e., 0dBm) also degrades packet delivery performance. When transmission power is -5.5dBm, we obtain the best performance. Based on this observation, we confirm that transmission power has potential to be optimized in a large scale industrial application which incurs heavy traffic near the root node. We further investigate the reasons of packet loss in the next subsection.

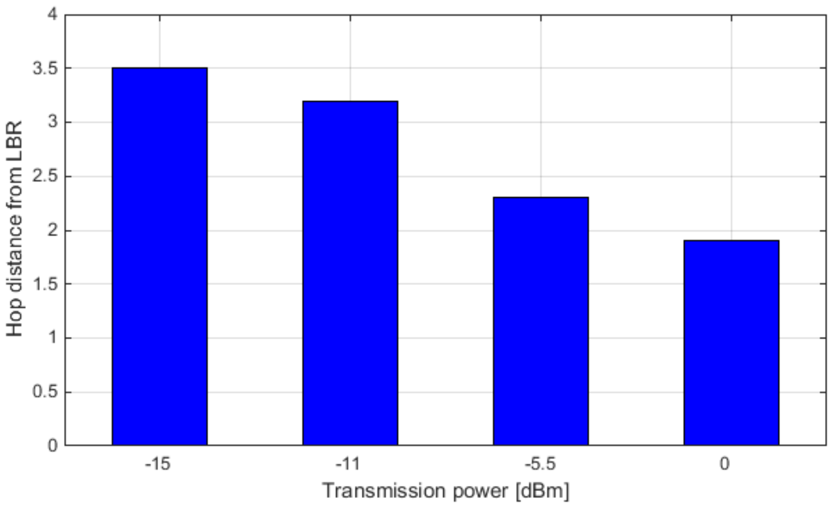

Fig. 3. Tx. power vs. Hop distance

From Fig. 3, we also confirm that hop distance decreases with transmission power. It is because increased transmission power enlarge transmission range, which allows long distance communication.

3.2. Queue loss and link loss

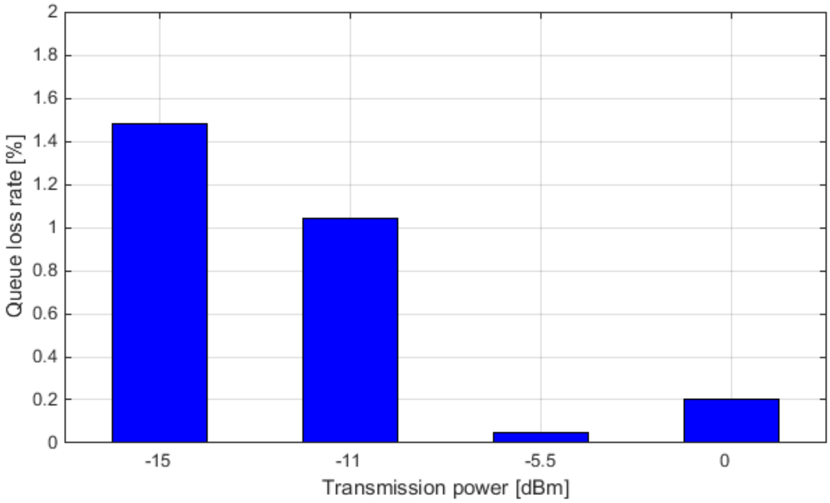

Fig. 4. Tx. power vs. Average queue loss rate

We divide the reasons of packet loss into the following two aspects: queue loss and link loss.

Queue loss: If the emission rate is higher than the transmission rate, a queue overflow will happen and as a result packets will be dropped, which is the reason for queue loss. This is the case that a packet is successfully received by a mote but has to be dropped due to queue overflow [10].

Link loss: If more than one sensor node in the same sensor network tries to transmit simultaneously, link loss will occur at the receiver. It is because that the acknowledgement message from parent node may collide with the data packets from children nodes. In addition, if many nodes try to send data packets simultaneously within range of the transmitting motes, interference may occur at the receiver.

It is possible to have both queue loss and link loss occurring at the same time.

Next, we will analysis queue loss and link loss by the results from real world experiments. We first analyze queue loss using Fig.4, which shows the average queue loss rate for different transmission power level. It shows that queue loss rate decreases as transmission power increases since hop distance and relay burden of each node decrease with transmission power.

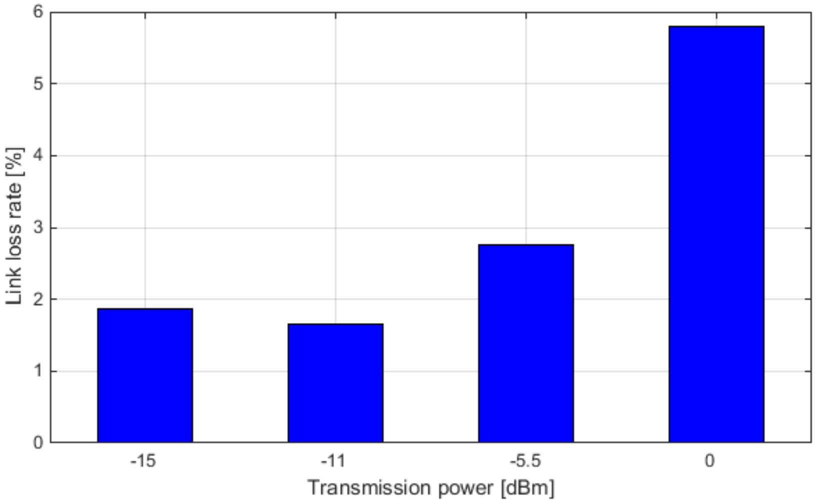

Fig. 5. Tx. power vs. Average link loss rate.

We move onto link loss analysis using Fig. 5, which illustrates average link loss ratio across different transmission power. We find out that link loss rate increases with transmission power due to packet collisions. We confirm the reason by counting average number of neighbors with varying transmission power. As transmission power increases, each node has more neighbors, which incurs congestion at link layer.

Overall, we confirm that trade-off between link and queue loss makes packet loss rate have a convex curve according to transmission power.

3.3. Topology analysis

Form Fig.6 and Fig.7, we can see node density is quite uneven due to obstacles. Look at Fig.7. Most of the nodes connected with node 19. Because RPL considers only hop distance and link quality for parent selection. Node 19 directly connected with the root, hence, node 19 has the lower rank and ETX value than other surrounding nodes. From this experimental results, we know RPL has load balancing problem in practice.

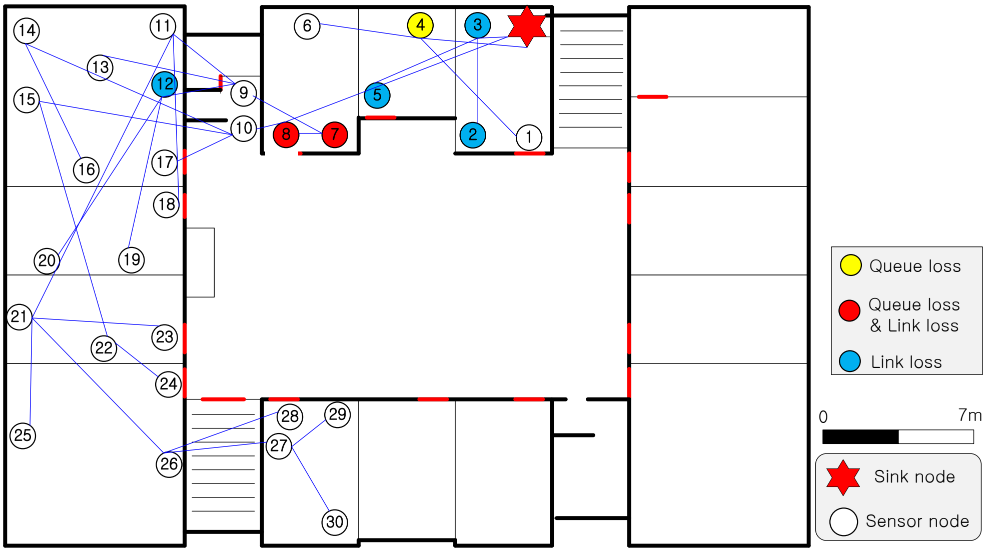

Fig.6 Snapshot when using Tx. Power -15 dBm

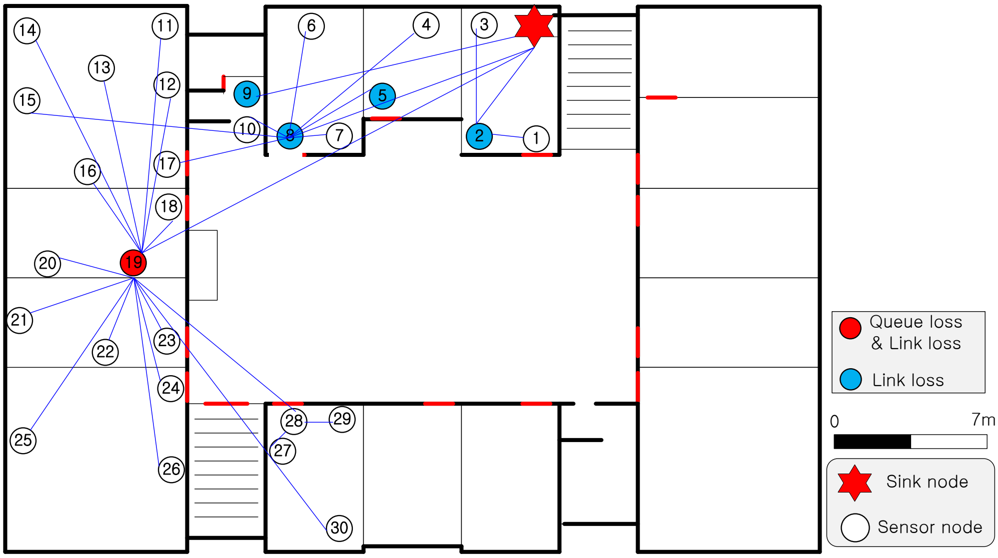

Fig.7 Snapshot when using Tx. Power 0 dBm

3.4. Per node analysis

We further investigate the characteristics of queue and link loss by per node analysis. Fig. 8 and Fig. 9 depict link and queue losses of each node with varying transmission power, respectively. Observing the experiment results, we find out that link and queue losses are significantly unbalanced among nodes, which shows the load balancing problem of RPL. Furthermore, queue loss occurs at the nodes which experience severe link loss. The correlation between link and queue loss allows each node to self-detect whether it suffers from congestion, regardless of its transmission power. Lastly, we observe that the nodes which experiences severe link and queue loss ratio vary according to transmission power. It shows that transmission power control heavily impacts on routing topology and has potential to enhance congestion problem.

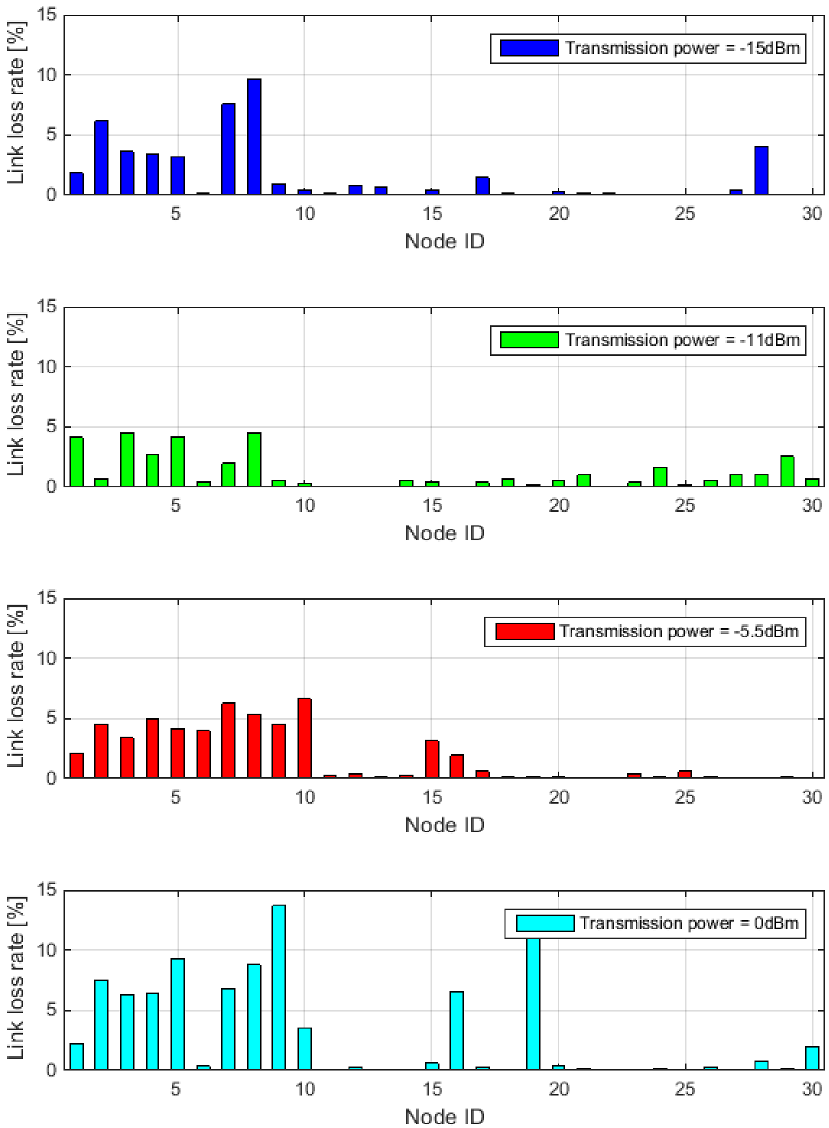

Fig. 8.Tx. power vs. Link loss rate of each node.

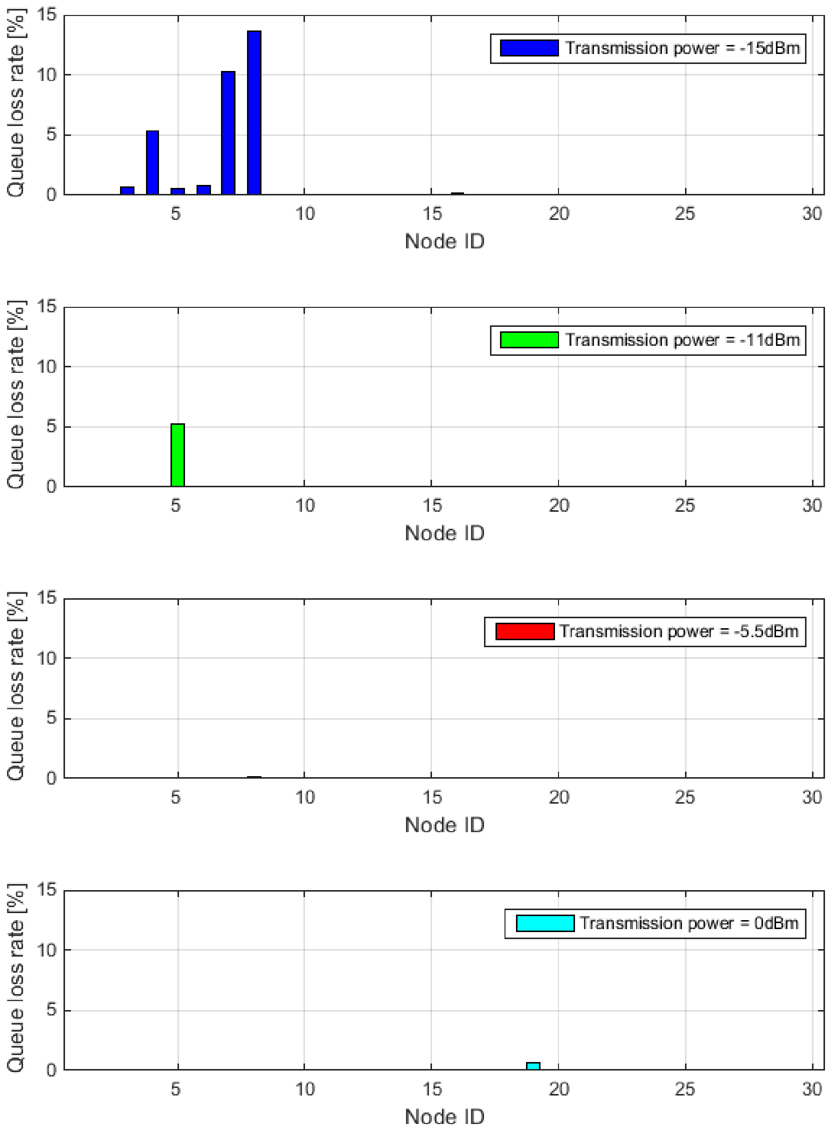

Fig. 9. Tx. power vs. Queue loss rate of each node

Chapter 4 Transmission Power Control Mechanism

As we has shown in last chapter, RPL has load balancing problem in all scenarios. In order to solve this problem, we try to use transmission power control mechanism, which allows the congestion node to reduce its transmission power, hence, it can detach its children nodes.

4.1 Effect of proposed power control on load balancing

We use three steps to express the effects of our power control on load balancing. We illustrate this process in the figures below. First step, when a node detects congestion, it reduces its transmission power. As Fig. 10 shows, node A will detect congestion due to its own link loss and queue loss and as a result node A reduces its transmission power according to our power control mechanism. Nest step, if network congestion or some interference happens to the sensor network, which keeps children nodes from transmitting data to the congested parent. Fig. 11 illustrates that node C cannot transmit data to node A due to network congestion. Node C will retransmit data to node A. The more retransmissions required, the higher ETX value will be calculated. If ETX value becomes higher, it means the link quality goes worse. And if retransmission number is bigger than specified number, the node will drop the packet, it leads to link loss. And node C cannot receive DIO message from node A because DIO power is reduced. Hence, Node C will change parent form node A to node B and construct a new DODAG as depicts in Fig. 12. That is to say, children nodes increase ETX for the congested parent node and change the parent.

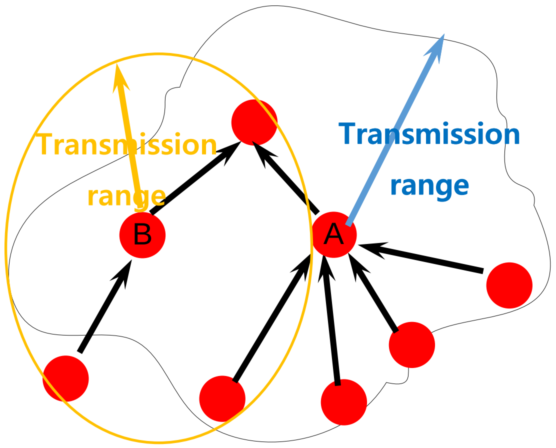

Fig. 10 First step: congestion detected

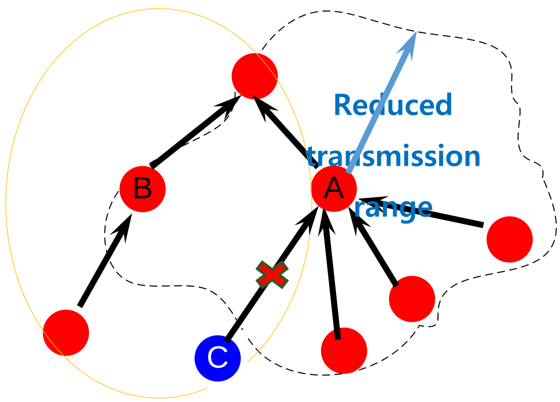

Fig. 11. Second step: ETX increase

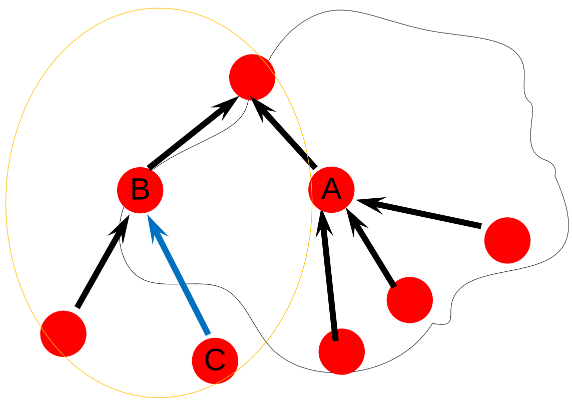

Fig. 12. Third step: Parent changed

4.2 Power control mechanism

After representing the effects of our power control mechanism, we will talk about the detail of proposed power control mechanism. We design a simple transmission power control mechanism which allows each node to adaptively control its transmission power according to its own queue and link losses. The main idea of our transmission power control mechanism is like Fig 13.

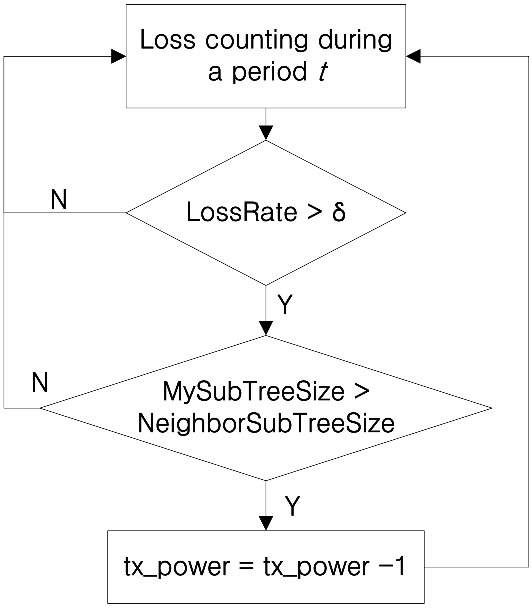

Fig 13. Transmission power control mechanism

Here, *loss* means the sum of queue loss and link loss, and *NeighborSubTreeSize* equals to sum of subtree size of same rank neighbors divided by number of same rank neighbors. Same rank neighbor indicates the neighbor node which has the same rank with me.

Power control mechanism works like below. First, we count loss during every time period of t by using a timer. According to the loss, we calculate *LossRate*, which can be obtained through loss divided by total transmission number. If

LossRate is bigger than δ, which denotes reliable criterion that we can preset according to different environments and requirements, we will go back to the timer. If current performance is better than before, we then will check whether *MySubTreeSize* is bigger than *NeighborSubTreeSize*. If *MySubTreeSize* is bigger than *NeighborSubTreeSize*, power index will be decreased by one, otherwise, go back to the beginning. If *LossRate* is lower than δ, we will return to loss counting stage. Each node runs transmission power control mechanism independently.

Each node is a TelosB clone device which supports CC2420. When dealing with the different 32 output transmission power levels that CC2420 supports, we set the maximum transmission power level to 31, which indicates 0 dBm, and the minimum transmission power level to 7 in our experiments, which is -15 dBm. We discard transmission power index form 6 to 0, because they are too small to send data packet in real test-bed environment that has different kinds of obstacles. The major parameter settings for power control are summarized in Table. 2

Table. 2. Parameter Settings for Power Control

Number of sensor nodes	30
Transmission power	-15 ~ 0 dBm
Traffic load	40 packets/min/node
Queue size	10 packets
reliable criterion	δ
Operating system	TinyOS-2.1.2
Timer	Period: 30 seconds

Chapter 5 Experimental Results

In this chapter, we analyze the performance of proposed method obtained from a multihop LLN test-bed, and compare it with standard RPL.

5.1. Changed transmission power and topology

Let's look at transmission power adjustment of each node after using transmission power control. From Fig. 14, we can see that each node adjusts its transmission power according to its loss rate. Here, loss indicates the sum of link loss and queue loss, and loss rate is the percentage of packets lost with respect to packets sent. The constrained node that has many children nodes will reduce its transmission power so that it can detach its children nodes to balance traffic loads.

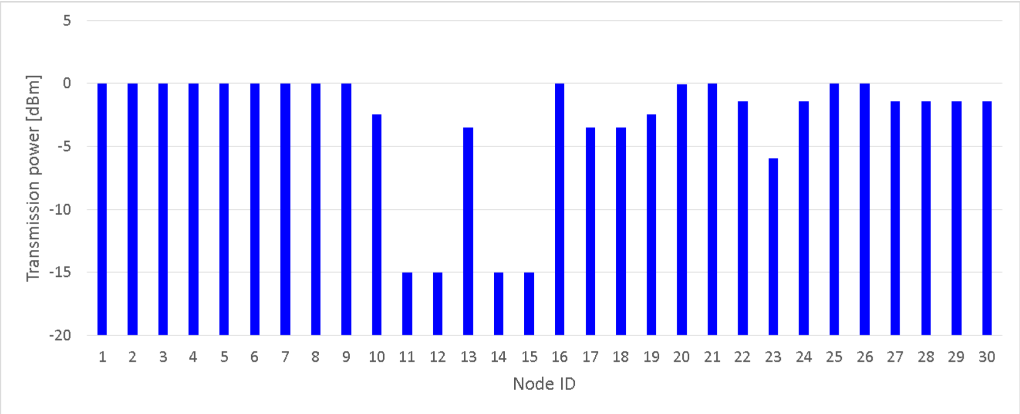

Fig.14 Changed Tx power

Proposed scheme can provide more balanced tree topology. Because each node can self-detect whether it is congested or not by using link loss and queue loss and if congestion is detected, the congested node will reduce its transmission power to detach its children nodes. We compare the effect of transmission power control mechanism by showing final topology of RPL and proposed scheme. Fig. 15 and Fig. 16 depict the snapshots of the routing topology at the end of experiments for standard RPL and proposed method. We graphically show the effect of proposed method on topology construction. From Fig. 15 and Fig.16 we find the maximum children number in final topology of RPL is 11, however, in proposed scheme is 8. From this result, we prove our proposed scheme has a good effect on load balancing.

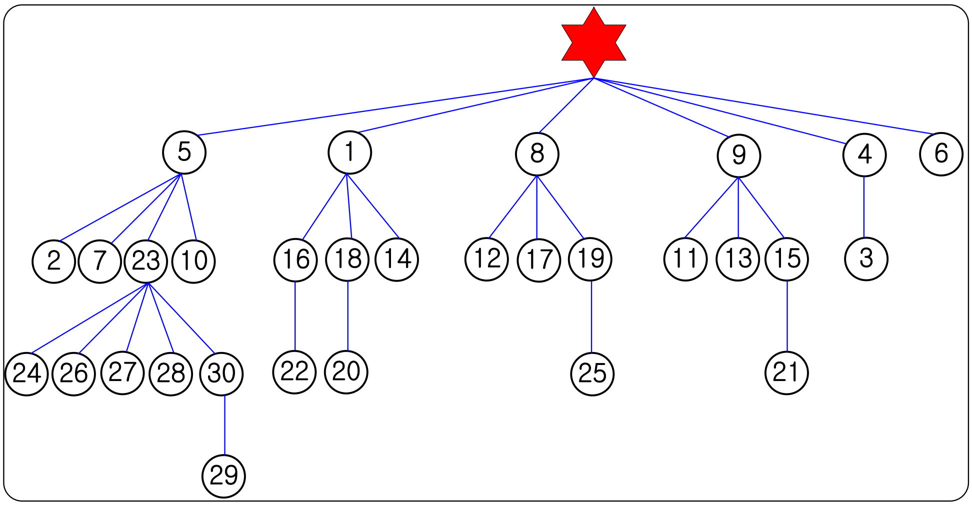

Fig.15 final topology of standard RPL

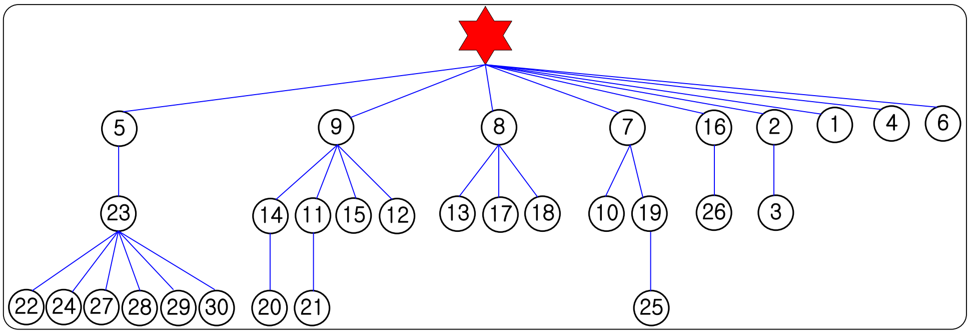

Fig.16 Final topology of proposed scheme

5.2. Queue loss and link loss

Let's move onto queue loss and link loss analysis using fig. 17 and fig. 18, which depict average queue loss rate and link loss rate for different transmission power level. We observed that proposed method reduces the queue loss ratio significantly as shown in Fig. 17. This reveals that our proposed power control mechanism has a critical impact on load balancing, and as a result, proposed method could provide lower queue loss compared to standard RPL. Proposed method dramatically reduces the traffic load of the nodes which have many children, while only slightly increasing those to nearby nodes. This is because proposed power control mechanism detaches its children nodes by reducing transmission power.

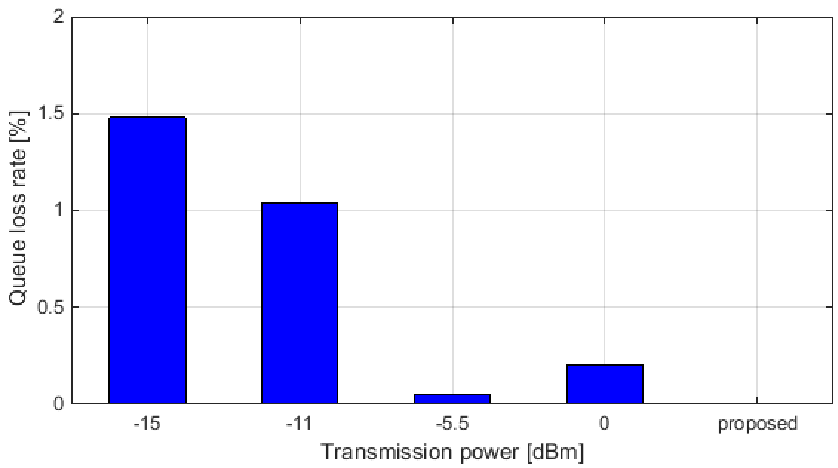

Fig17. Queue loss rate vs. Tx. Power

Fig. 18 compares the average link loss ratio of different transmission power in standard RPL with proposed method. We observe that in standard RPL, link loss rate increases when increasing transmission power due to packet collisions, however, under transmission power controlling, link loss rate turns out to be the lowest. We find out that the nodes which have many children suffer link loss seriously. As transmission power increases, transmission range will increase hence each node has more neighbors, which incurs congestion at link layer. In order to solve this problem, proposed method allows each node reduces its children number by controlling its transmission power adaptively according to its own congestion condition. Therefore, traffic congestion of the most constrained node is reduced at the same time while only slightly increasing other nodes traffic.

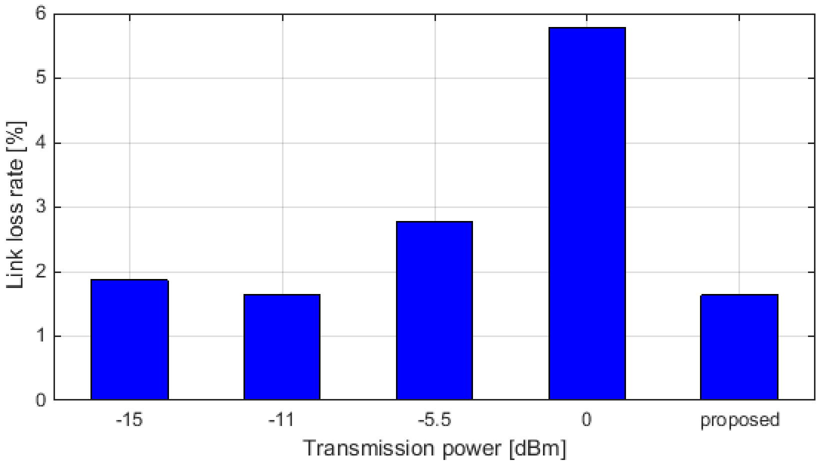

Fig18. Link loss rate vs. Tx. Power

Overall, we observed that the combining queue loss and link loss together makes packet loss rate have a convex curve according to transmission power. Next, we will talk about packet loss rate in detail.

5.3. Packet loss rate

In this subsection, we analysis packet delivery performance of proposed method. In accordance with our previous analysis, when the transmission power at each node is small, many data packets are dropped due to relay burden, resulting in high packet loss ratio. This conclusion is also supported by the experimental results of subsection 5.2. By increasing transmission power, packet loss rate first decreases and increases again. When using power control mechanism, packet delivery performance is much better than the performance of standard RPL under the same configuration. This is because in standard RPL, some sensor nodes are so heavily congested that even increasing the transmission power cannot alleviate the congestion caused by load imbalance.

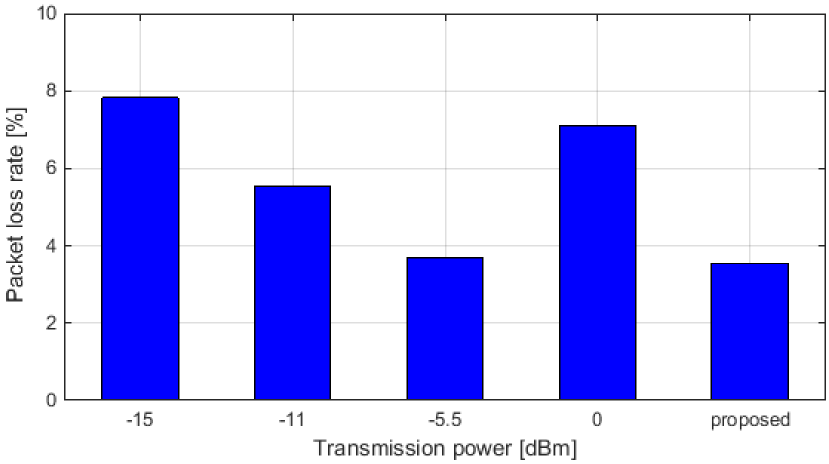

Fig19. Packet loss rate vs. Tx power

Fig. 19 depicts packet loss rate of the real-world sensor network test-bed under different transmission power settings. From this result we can observe that proposed method exhibits the much lower packet loss than the standard RPL protocol. This is because by balancing the workload among sensor nodes power control essentially helps reduce congestion. As a result, packets will not be queued or collided in some sensor nodes for a long time.

Chapter 6 Conclusion

In this paper, we have propose a power control mechanism based on RPL protocol to achieve congestion avoidance and load balancing among sensor nodes in large scale low power and lossy networks. We have verified that packet delivery performance at heavy load first increases and then decreases with transmission power and have proved the use of maximum transmission power in RPL cannot provide the best performance. To investigate the reasons of what and how the convex curve happens, we have shown a trade-off between queue and link losses according to transmission power. We have found that link loss has dramatically increased with transmission power, on the contrary, queue loss has decreased with transmission power. According to the characteristic, we have designed a lightweight power control mechanism based on the standard RPL protocol, which allows each node to adaptively control its transmission power according to its own queue and link losses, to achieve balanced workload distribution among nodes in large scale low power and lossy networks. Load balancing and congestion condition are jointly considered to control transmission power for maximizing packet delivery performance. We have confirmed that power control mechanism improves performance through real-world testbed experiments in comparison to the standard RPL protocol. Test-bed experimental results show that the proposed power control mechanism performs much better than standard RPL protocol in terms of load balancing and packet delivery performance.

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초 록

저전력 손실 네트워크에서 대규모 응용분야를 위한 전송전력 제어기법

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저전력 손실 네트워크에서 전송파워는 라우팅 토폴러지를 결정하는데 아주 큰 영향을 준다. 전통적으로 저전력 손실 네트워크는 낮은 속도의 트래픽을 위하여 설계되어왔다. 이런 트래픽 상황에서는 파워를 크게 쓰면 쓸수록 좋은 성능을 가져올 수 있었는데 이것은 파워를 높이면 홉 거리를 줄일 수 있고 전송 오버헤드를 줄일 수 있기 때문이다. 그러나 규모가 큰 응용분야에서는 저전력 손실 네트워크가 높은 속도의 트래픽을 전송하는 것을 요구한다. 이런 대규모 응용분야에서 각 노드가 낮은 속도의 트래픽을 생성한다 할지라도 루트와 가까운 노드들은 많은 트래픽을 전송하게 된다. 결론적으로 이런 노드들은 링크 혼잡을 겪게 된다. 본 논문에서는 먼저 테스트베드 상에서 높은 트래픽 환경의 실험을 통하여 전송파워가 저전력 손실 네트워크의 표준 라우팅 프로토콜(RPL)에 준 영향을 연구하였다. 낮은 속도의 응용분야와 달리 높은 속도에서의 실험결과를 보면 전송파워가 커짐에 따라서 패킷 전송 성능은 좋아졌다가 다시 나빠졌음을

발견하였다. 그리고 패킷 손실율이 컨벡스 형태로 나타나도록 만든 원인을 확실히 파악하기 위하여 패킷 손실이 어떤 식으로 발생하는지를 노드별로 분석하여 확인해보았다. 우리는 손실을 링크 손실과 큐 손실로 구분해서 분석해보았으며, 실험의 결과로 링크 손실과 큐 손실은 불균형하게 각 노드에 분포됨을 확인하였다. 이는 RPL의 부하 불균형 문제를 보여준다. 뿐만 아니라 링크 손실을 심하게 겪는 노드에서 큐 손실이 많이 나타났다. 이 문제를 해결하기 위하여 우리는 간단한 파워 컨트롤 방법을 제안하여 각 노드들이 자신의 링크 손실과 큐 손실에 따라서 적응적으로 자신의 파워를 제어하여 라우팅 트리의 트래픽 부하를 균등하게 분배하게 함으로써 패킷 전송 성능을 높였다. 우리는 실제 멀티 홉 저전력 손실 네트워크 테스트베드에서 IEEE 802.15.4 기반의 RPL을 실행하여 성능향상을 보였다.

Keywords : RPL, low power and lossy networks, transmission power, reliability, load balancing, wireless sensor networks

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