Improving IEEE 802.11s Wireless Mesh Networks for Reliable Routing in the Smart Grid Infrastructure

Conference Paper · July 2011

DOI: 10.1109/iccw.2011.5963578 · Source: IEEE Xplore

6 authors, including:

Keun-Woo Lim
Ajou University

Young-Bae Ko
Ajou University

Kim Younghyun
Korea University

Improving IEEE 802.11s Wireless Mesh Networks for Reliable Routing in the Smart Grid Infrastructure

Ji-Sun Jung, Keun-Woo Lim, Jae-Beom Kim, Young-Bae Ko
Graduate School of Information and Communication
Ajou University, Suwon, Korea
{mesameme, kwlim27, jaebeom, youngko}@ajou.ac.kr

Younghyun Kim, Sang-Youm Lee
Green Growth Laboratory
Korea Electric Power Research Institute, Korea
{04100212, wifi2}@kepco.co.kr

***Abstract*—Smart grid environments require high standard of reliable transmission technologies to support various types of electrical services and applications. This paper recommends the utilization of IEEE 802.11s based Wireless LAN Mesh Networks as the high-speed backbone networks for smart grid infrastructure. 802.11s based mesh networks can provide high scalability and flexibility, along with low installation and management costs. We also describe some challenging issues of the IEEE 802.11s WLAN mesh based smart grid networks, and propose two novel methods for improving the routing reliability. A simulation study using the *ns-3* was conducted to evaluate the problems in the current mesh networks and prove the superiority of our proposed scheme.**

Keywords – Wireless Mesh Networks; Smart Grid; IEEE 802.11s; Reliable Routing

I. INTRODUCTION

Wireless Mesh Networks are becoming one of the core technologies for realization of next-generation networking technology. Wireless Mesh Networks can provide high-speed and reliable wireless transmission methods in various types of applications, such as wireless Internet service, disaster relief, military surveillance and reconnaissance, and etc. In many cities various forms of wireless mesh networks are already deployed and verified [1].

One of the promising application domains of wireless mesh networks is the *Smart Grid*, which is defined as an electrical system or infrastructure that fuses with communication technologies to support transmission of electrical information and provide remote power management [2]. From the wireless networking perspective, smart grid can enable different types of technologies for different requirements of the network. This is because the basic networking architecture of the smart grid is constructed in a hierarchical manner. A general approach shown in [3] distinguishes each hierarchy as the Home Area Network (HAN), Neighbor Area Network (NAN), and Wide Area Network (WAN), each utilizing different types of networking technologies that are suitable for their needs. For example, the HAN focuses on the small scale data communication between devices inside typical households. These data may include power metering data, on-demand electric billing system, in-home energy displays, and etc. In many aspects, the IEEE 802.15.4 based ZigBee [4] technology is currently thought of as the ideal candidate for these small-scale, short range networks. The WAN becomes the backbone system combining the HAN and NAN. Due to this nature, technologies such as 3G or Ethernet are considered as the default systems for WAN.

The NAN, the area where this paper has its focus on, receives data from multiple HANs and provides a backbone for these data to be transferred high-speed to electric substations and electric providers. Furthermore, NAN also maintains its own applications, such as power status management and monitoring, and power substation surveillance. Most of these data are often transmitted in a periodic manner, but they can also be requested on-demand by a server using request queries.

These kinds of data traffic characteristics make NAN a very unique type of networking environment, compared to other traditional wireless networking applications. Firstly, it is required for the NAN to be able to differentiate these various types of data in its network, and provide high level of QoS for more time-critical traffic. Secondly, due to the commercial properties of smart grid, it is essential to provide very high reliability for transmission of its data. Also, bulks of periodical data generated by NAN nodes are constantly transmitted upstream to the server, often causing concentration and congestion near the area of the server. Due to these properties, technologies such as the wireless mesh networks can be considered as the candidate for providing high-speed and easy-to-deploy wireless backbone in NAN [5].

Some work such as [6] proposes mesh based routing methods for vast scale AMI data transfer, and various manufacturing companies such as Tropos [7] and Trilliant Inc. [3] have presented their own proprietary solutions for utilizing mesh networks in NAN. While these propositions may seem unique and innovative, they do not design a precise architecture of the mesh technology, stating vaguely that various forms of 3G, WiMAX, or WiFi can be possible candidates for the job. It is important that this area of mesh networking is based on a single superior technology that can provide better scalability between smart grid applications and easier world-wide deployment of the technology.

To support reliable and high-speed transmission for smart grid networks, IEEE 802.11s [8] can be a potential candidate for efficient configuration of mesh networks in NAN. The 802.11s standard provides an efficient form of multi-hop routing called the Hybrid Wireless Mesh Protocol (HWMP) and unique topology formation methods. These functions of the 802.11s and HWMP can be expected to support the various requirements of NAN in smart grid. The characteristics are shown below:

This research was in part supported by the R&D program of KEPCO (Korea Electric Power Corporation), Korea (Development of Integrated data communication networks for smart-grids) and Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0016189).

978-1-61284-953-9/11/$26.00 ©2011 IEEE

- ➢IEEE 802.11s utilizes the EDCA scheme originally defined in IEEE 802.11e [9] standard to differentiate data traffic by priority and provide QoS for time-critical data, which is also a typical requirement in NAN.
- ➢The hybrid transmission policy and airtime cost metric in HWMP are considered to be suited to static mesh networks, which is also a characteristic of NAN.
- ➢The gateway-to-mesh node association of the mesh network in 802.11s provides an idealistic topology for NAN. For example, periodic upstream data generated by NAN nodes can be constantly transmitted through the gateway and to the server that is wired to the gateway.

Considering these properties, the 802.11s can indeed be the right technology for smart grid environments. However, some problems arise when the typical form of 802.11s mesh networks are implemented in the smart grid environment. Firstly, the 802.11s standard specifies a default routing link cost metric that may not be perfectly suitable in the unique smart grid environment. Also, the route instability problem [10] can occur while utilizing the HWMP in the 802.11s further degrading the network reliability and throughput. We try to tackle these problems, and then propose solutions that can alleviate the problems and improve the overall efficiency of the mesh network. The proposed methods are evaluated using the *ns-3* simulator [11] to prove that they can be beneficial in realizing the deployment of 802.11s in the smart grid systems.

II. Background and Problem Statement

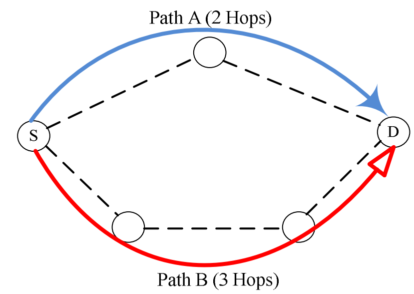
A. IEEE 802.11s and HWMP

The IEEE 802.11s draft for WLAN mesh standards defines the architecture and protocols that are suitable for wireless multi-hop mesh networking environments. The topology of 802.11s mesh is built upon a central mesh gateway which provides wireless connections to mesh stations. Mesh access points act as the terminals to client devices and provide various services via multi-hop transmission with the gateway and the mesh stations.

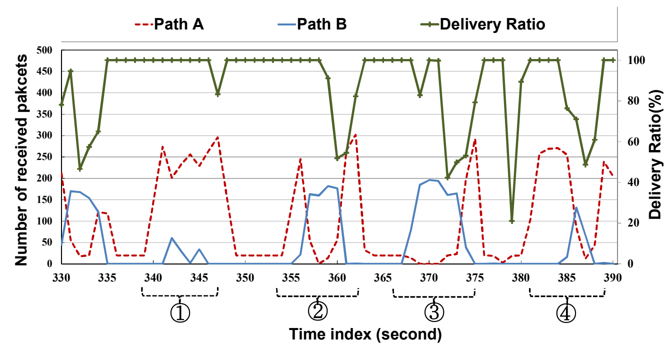
Multi-hop routes are created using the HWMP which is the default path selection protocol. The HWMP combines two types of routing modes: the on-demand mode and the proactive tree building mode. The proactive tree-based routing mode is designed to work with the Root Announcement (RANN) mechanism. Upon utilization of the RANN mechanism, the gateway floods the network with RANN messages. This packet is then received and relayed by all the sub-nodes of the mesh network. Upon reception, each mesh node will calculate the *airtime cost metric* shown below:

$$c_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f} \qquad (1)$$

, where O = channel access overhead, B_t = size of the transmission frame, r = data rate, and e_f = error rate. Therefore, the airtime cost, as the name implies, will represent the latency and the error rate of a specific multi-hop path while the data packets are transmitted wirelessly through the route. This information is calculated at each mesh node and cumulated inside the received RANN packet. Each node will use the cumulated airtime cost information in the RANN packet as well as its own airtime cost calculation to choose the most efficient multi-hop route to the gateway. Via periodic RANN transmissions, all nodes will regularly update the best single multi-hop route to the gateway. When the path to the root is considered obsolete due to transmission failure, a new path is discovered before the RANN period using an on-demand path discovery algorithm identical to the traditional AODV [12].



(a) Topology used for problem evaluation



(b) Effects of Route Fluctuation in the network

Fig. 1 Evaluation of Route Fluctuation in 802.11s

B. Problems in IEEE 802.11s

Even though 802.11s can be considered suitable for smart grid networks, new problems can also be generated in the integration process. Also, some old and existing problems of the 802.11s prevail to degrade the performance of the network. The calculation of the airtime cost will reflect the first described problem. The method of error rate calculation in equation (1) is not specified in the standard draft, leaving the problem as an open issue. One representative method of calculating this link cost can be observed in the Open11S project [13], which uses unicast data packet error ratio to calculate its current error rate. However, we believe that this common metric cannot be efficient in the smart grid environment where variety of different applications with different packet sizes may be generated, because it will treat each packet as though they are the same. Another metric calculation method that utilizes small control packets to calculate the error rate [14] cannot also be optimal solution, because data packets tend to be much larger than these control packets. Therefore, new methods of calculating the error rate for the airtime cost calculation in smart grid environments are needed.

The problem of route instability in HWMP is an example of an existing problem in the traditional mesh networks [10] which is critical in smart grid environments. The route instability problem occurs when the routing path of a node constantly changes during data transmission, even when the current route can be utilized without any severe problem. This phenomenon occurs because the transmission of the data actually causes the current route link cost to degrade. We have analyzed the problem using the ns-3 [11] simulator, as shown in Fig. 1. We have configured a simple multi-hop topology where a mesh node can transmit data to the destination via path A which is a 2-hop route and path B which is a 3-hop route, as shown in Fig. 1 (a). The link cost of the routes is updated every two seconds. Traffic models identical to smart grid applications are used for the transmitting node, which we give more details in Section 4.

Fig. 1 (b) shows the effects of route instability on the overall network performance. During the simulation of 500 seconds, we zoom in on the 330-390 second interval, which is severely affected by the route instability. Here we can see that even though the 2-hop path that guarantees less link cost should be utilized as shown in interval ①, the less efficient 3-hop path is utilized instead at intervals ②, ③, and ④ of the network. This is because the current transmission through the 2-hop path temporarily degrades the link cost of the path. Even though packet delivery ratio is nearly 100% in interval ①, mistake in the current link cost calculation makes the protocol to select the 3-hop path. Therefore, we can clearly see that the packet transmission rate and the delivery ratio in intervals ②, ③, and ④ are decreased compared to interval ①. [10] defines the same problem shown in Fig. 1 on actual mesh network testbed modeling, but does not provide a method of solving this problem. To alleviate this problem, we present some methods that can be utilized in the smart grid system.

III. Proposed Scheme

The proposed scheme tries to alleviate the route fluctuation problem by using two methods: The modification to the current airtime cost metric calculation method defined in the 802.11s standard, and the route fluctuation prevention algorithm. The first scheme suggests a new method of calculating the error ratio of each node that can be more suitable in smart grid environments. The second scheme provides a module for suppressing the amount of fluctuation by considering the previous route selection histories.

A. Airtime Cost Modification

Majority of the data in Smart Grid environments are considered to be upstream and therefore these properties must be considered in the airtime cost calculation. To consider this property, we select the MAC retransmission count of each packet as the value for calculating the failure rate of the network. This parameter will account for all types of transmission failures that cause a MAC retransmission, such as packet collisions and bad channel conditions [15]. In the 802.11 standard [16], a node will attempt to transmit its data frame until it receives an ACK frame from the next-hop node. Therefore, the number of retransmissions that has been made to deliver a data frame can be used to calculate the failure rate of the current network, as shown in (2):

$$e_f = \frac{M_n \times \frac{1}{P_n}}{R_{\max}} \tag{2}$$

, where M = total number of MAC level retransmissions made by node n, P = total number of packets transmitted by node n, and $R_{\max}$ = allowed maximum retransmission count. By using this metric, we put more focus on the upstream transmission status. This is because even though a packet may have successfully been transmitted to another node, it may have triggered many MAC level retransmissions for successful transmission of the data. Too much retransmission may cause interruptions in other transmissions and also become more prone to failures in future data transmissions. We believe that this retransmission value can be more accurate for Smart Grid environments where precise calculation of the current radio status is needed for reliable data transmission.

When considering the smart grid environment, it is important to note that a single smart grid infrastructure may provide services to various applications, and therefore various data types may be simultaneously be transmitted inside the network. These different data types may vary in packet size, and it would be unfair to treat the MAC retransmission level of each of these different data identically. For example, a small packet with size of 123 bytes should not be considered identically with a large packet of size 1024 bytes. We can safely assume that retransmission of a small packet is more critical than the retransmission of a large packet, because smaller sized packets are less prone to bit errors. To give various penalties to the airtime cost calculation when considering the sizes of each packet, we change the equation (2) to (3):

$$e_f = \frac{\sum_{i}^{Pn} M_i \times (1 - \frac{B_i}{B_{\max} + B_i})}{P_n R_{\max}} \tag{3}$$

, where B_i = size of the packet i in bytes, $B_{\max}$ = the biggest size of the packet in the network which we configure as 1024bytes, the default MPDU in [16]. By using equation (3) we can consider the penalty of each packet depending on its size. For example, the packets with size of 1024bytes will receive the minimum penalty value of 0.5, while smaller packets will receive a penalty close to 1, which is the maximum penalty value. The total value of the error rate will always result between 0 and 1, and thus can be inserted in the error rate parameter in equation (1) to ultimately calculate the airtime cost. This approach, compared to [15] where the metric is targeted for typical mesh networks, can be considered more beneficial in the smart grid environment.

B. Route Fluctuation Prevention

To reduce the route fluctuation and improve the performance of the network, we propose a modification to the route selection method in HWMP. Even though a node may receive multiple RANN messages from multiple neighbor nodes, the current route selection method in HWMP allows a node to maintain only one optimal route in the routing table. For our algorithm to function, we have modified and extended the route table of HWMP so that multiple route information in the current RANN interval as well as the information from the previous RANN interval is stored by each node. Each mesh node will maintain and update the airtime cost of all the RANN messages that it receives: the current path calculated from RANN in the current interval, multiple reserve paths calculated from RANN in the current interval, current path calculated from the previous RANN interval, and multiple reserve paths calculated from the previous RANN interval. Using the airtime cost of these routes, Algorithm 1 is used to select the new route.

From the algorithm, we can see that the current path is maintained if it has lower airtime cost than the reserve paths. However, if the cost of a reserve path is lower than the airtime cost of the current route, the airtime cost of the previous interval is then checked. The variation between the previous RANN interval and the current RANN interval of each path is compared and switched if the variation of the airtime cost in the current path is higher than the variation of the reserve path.

However, if the link-cost variation of the current route is less than the reserve route, the current route will be maintained. By utilizing the algorithm, we can reduce the frequency of route fluctuation as the reserve routes will not be selected whenever it has a better airtime cost. Furthermore, the conditions also allow the route to be switched if the current path becomes too degraded and better paths exist.

IV. PERFORMANCE EVALUATION

The performance of the proposed scheme is evaluated via the ns-3 simulator. The IEEE 802.11s standard implemented in the simulator was modified and used to compare our scheme with the original version. 802.11a PHY layer was used with a bit rate of 54Mbps. Each mesh node that represents a NAN node will transmit data using the smart grid application set that we have configured, as shown in Table 1. We have configured the applications according to the smart grid information from KEPRI [17].

In Table 1, AMI data can be thought of as data from HAN nodes, while power quality and video surveillance data are NAN applications. On-demand applications are generated randomly by each node in the network, while periodic data will be constantly transmitted by all the nodes. All applications are generated with the root gateway as their destination, and are configured as CBR traffic.

Algorithm 1: Route Selection in HWMP

SelectRoute – for each reserve path in the routing table,

if $path_{curr}(C_{an}) \le path_{res}(C_{an})$

  select $path_{curr}(C_{an})$ *as* $path_{curr}(C_{an})$

else if

  if $path_{curr}(C_{an} - C_{an-1}) \le path_{res}(C_{an} - C_{an-1})$

    select $path_{curr}(C_{an})$ *as* $path_{curr}(C_{an})$

  else

    select $path_{res}(C_{an})$ *as* $path_{curr}(C_{an})$

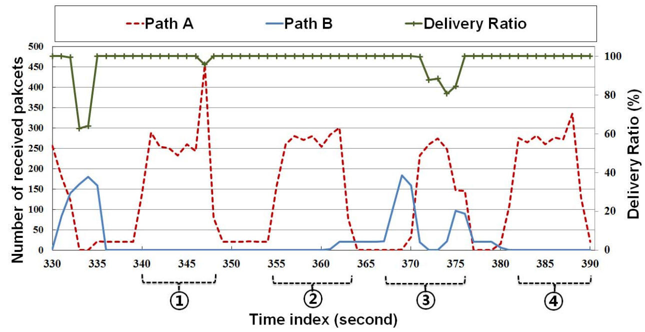


Fig. 2 Route Fluctuation in the proposed scheme

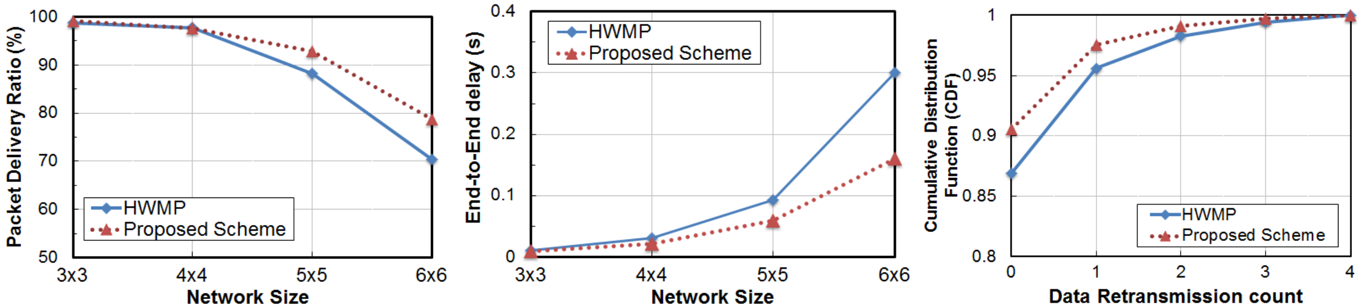
Table 1. Smart Grid Application Set

Type of Service	Transmission Interval (s)	Application Size (Bytes)
AMI Data	15	123
AMI Request Data	On-Demand	123
AMI Management	300	4000
Power Quality Data	3	3000
Power Quality Request Data	On-Demand	2000K
Power Management	300	4000
Video Surveillance	On-Demand	2500K

Firstly, we analyze the impact of our scheme in the simple topology shown in Fig. 1. Fig. 2 shows the route fluctuation of our proposed scheme, and we can see that route fluctuation does not occur in the intervals ② and ④, which is a different phenomenon compared to the results in Fig. 1 (b). Also, in interval ③, even though path B is used from time to time, majority of the data is still transmitted through the more efficient path A and provides better throughput and delivery ratio than the traditional HWMP.

The next set of simulation analysis uses a more complex scenario to evaluate the performance of our scheme. Nodes were laid out on the network in a grid topology, and simulations were made using 9, 16, 25, and 36 nodes. The node at the center of the grid becomes the data collecting root node. The amount of traffic generated in this environment will cause congestion in the network when 25 or more nodes are deployed.

Fig. 3 shows the result of the simulation between the proposed scheme and the traditional HWMP protocol. Three types of comparisons are made, which are packet delivery ratio, end-to-end delay, and the data retransmission count. Packet delivery ratio represents the percentage of data packets that are successfully transmitted from source node to the destination node. End-to-end delay represents the average time that is taken for a packet to successfully reach the destination node via multi-hop. The data retransmission count shows the cumulative distribution function of all the packets, which counts the amount of mac level retransmissions that each packet has used for successfully transmitting its data to the destination node.



(a) Packet delivery ratio (b) End-to-End delay (c) Data Retransmission count

Fig. 3 Performance Evaluation of the Proposed Scheme in comparison to HWMP

Fig. 3 (a) shows the reliability of the two protocols by measuring the packet delivery ratio. Both methods can guarantee nearly 100% of reliability when there are 9 to 16 nodes deployed in the network. However, the packet delivery ratio is declined when more mesh nodes are deployed and congestion starts occurring in the network. Due to poor route selection and route instability, the decline ratio in the HWMP is steeper than the proposed scheme, showing that our scheme guarantees higher reliability. This is because the HWMP cannot frequently utilize better routes due to more route fluctuation, causing more packets to be transmitted through links with higher cost. On the other hand, the proposed scheme can provide higher delivery ratio even when there is severe congestion in the network, because better decisions are made in route selection using the proposed route stability algorithm.

Fig. 3 (b) shows that higher reliability also guarantees better end-to-end delay for our proposed scheme. This is because the selection of better routes from prevention of fluctuation allows faster data transmission, while the routes selected by the HWMP will cause more collisions and mac level retransmissions, which can consume much more time for transmission at each hop. Even though the HWMP can still provide acceptable delay values, we can clearly observe that the modifications we have made can further improve the latency ratings of each packet.

Fig. 3 (c) shows the effect of our proposed link cost metric calculation in a network with 25 nodes deployed in a grid formation. Over 90% of the packets in the proposed scheme are transmitted with no mac level retransmissions, which mean that the data has been transmitted successfully without any retransmission attempt. However, the common HWMP model guarantees about 86% of no mac level retransmissions, and more packets have attempted one, two, or even three retransmissions to successfully transmit a single packet. Since more retransmissions can cause more distractions in the signals and consume more bandwidth, our proposed scheme which uses less retransmission can be thought of as more ideal in smart grid environments. In overall, we can conclude that our proposed scheme can reduce fluctuation, improve reliability, and improve the overall efficiency of the smart grid network.

V. Conclusion

Wireless Mesh Networks utilizing the IEEE 802.11s standard can provide high reliability as well as high performance in the smart grid networking environment. However, this assumption can only be valid when important modifications are made within the standard considering the dynamic environment of the smart grid. This paper introduces the possibility of utilizing standard based mesh networks in the smart grid and provides methods to improve the performance of the smart grid network. However, the proposed scheme also cannot guarantee optimal reliability, as shown in Fig. 3 (a) where the packet delivery ratio also decreases when there is congestion in the network. Therefore, improving this reliability factor via modifications in the routing algorithm will be our future work. Also, better support is needed for handling priority-based transmission for various applications in smart grid.

References

[1] G. Vasilakis, G. Perantinos, I. Askoxylakis, N. Mechin, V. Spitadakis, A. Traganitis, "Business opportunities and considerations on wireless mesh networks," IEEE WoWMoM, 2009.

[2] K. Moslehi, R. Kumar, "A Reliability Perspective of the Smart Grid," IEEE Transactions on Smart Grid, Vol. 1(1), pp. 57-64, 2010.

[3] Smart Grid Communications Network, *http://www.trilliantinc.com/*.

[4] ZigBee Alliance C, *http://www.zigbee.org*

[5] Mesh Networks in Communications Winner in Utility Survey, *http://www.smartgridnews.com/artman/publish/Technologies_Communications_News/Mesh-Networks-Is-Communications-Winner-in-Utility-Survey-1645.html*.

[6] T. Iwao, K. Yamada, M. Yura, Y. Nakaya, A. Cardenas, S. Lee, R. Masuoka, "Dynamic Data Forwarding in Wireless Mesh Networks," IEEE SmartGridComm, 2010.

[7] GridCom Tropos, *http://gridcom.tropos.com/*

[8] IEEE P802.11s™/D7.0, Draft amendment to standard IEEE 802.11™: Mesh Networking. IEEE, 2010, work in progress

[9] IEEE 802.11, "Amendment 8: Medium Access control (MAC) Quality of Service Enhancements," IEEE Std 802.11e-2005.

[10] K. Ramachandran, I. Sheriff, E. Royer, K Almeroth, "Routing stability in static wireless mesh networks," Passive and Active Network Measurement," Vol. 4427, pp. 73-82, 2004.

[11] Ns-3.8, "The ns-3 network simulator," *http://www.nsnam.org*, May 2010.

[12] C.E. Perkins, E.M. Royer, "Ad-Hoc On-demand Distance Vector Routing," RFC 3561, 2003

[13] Open 802.11s, *http://www.o11s.org/*

[14] Z. Shang, J. Wang, H. Yu, "Cross-layer Enhancement to Multi-hop Routing in Sensor Networks: an Empirical Study," Acta Automatica Sinica, Vol.32 (6), pp. 875-880, 2006.

[15] D. Guo, J. Li, M. Song, J. Song, "A Novel Cross-Layer Routing Algorithm in Wireless Mesh Network," IEEE ICPCA, 2007.

[16] IEEE P802.11. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, 1999.

[17] Korean Electric Power Research Institute, *http://www.kepri.re.kr/*.