Hierarchical wireless network architecture for factory network

Sungnam Moom, Younghan Kim

(*School of Electronic Engineering, Soongsil University, Dongjak-gu, Seoul 156-743, Korea*)

Abstract: The traditional wired networks in an industrial firm often encounters large difficulties, such as the cable installation, regular maintenance and cable replacement and so on, all these results in high cost. So, in this paper, we propose an IP-based hierarchical wireless network architecture and apply some of the technologies of 6LoWPAN to it. We verify the proposed architecture via real implementation with a wireless backbone, sensor networks and a connection between those networks. And the IP-based hierarchical industrial network is indeed an advanced network for harsh industrial environments.

Key words: wireless sensor network; factory network; 6LoWPAN; routing protocol for LLN (RPL); constrained application protocol (CoAP); wireless mesh network (WMN)

CLD number: TP393 **Document code:** A
Article ID: 1674-8042(2012)02-0163-06 **doi:** 10.3969/j.issn.1674-8042.2012.02.013

The traditional architecture for a large-scale industrial network has a hierarchical and heterogeneous network structure.

An industrial network has a hierarchical network architecture. Devices, such as sensors, actuators and control and monitoring systems, compose a unit domain network. A plant backbone network connects the external network and the Internet to unit domains and also connects them to each other. The plant backbone also has heterogeneous network architecture. Heterogeneous sensors help the unit domain network to comply with other network requirements and components.

In general, wireless technology is partially applied to a harsh industrial environment, and the wired network is applied to the control system, the management system and the industrial plant backbone. An industrial firm often encounters large difficulties in expanding its wired industrial network, because the cable installation for communication and power requires the high cost. Worse still, the harsh industrial environment demands regular maintenance and cable replacement, which also results in high cost.

Devices in a unit domain network can be managed not only inside a system on the plant network but also through a system on the exterior networks. Moreover, the plant personnel must have ability to monitor and control the device in the field through their own devices. Therefore, the personnel must have access to seamless communication between devices and systems in different unit domain networks. The end-to-end communication between heterogeneous networks makes an edge router harder to implement.

An industrial network must be flexible and its operation should base on the given network topology. And it must remain stable in a harsh environment and be scalable for large-scale deployment, and must support a seamless connection with other networks, such as Internet, wireless fidelity (WiFi) and wireless broad-band (Wibro)[1-3], (i. e. scalability, flexibility, mobility and cost-efficiency).

In this paper, we propose the IP-based hierarchical wireless network architecture that is suitable for the aforementioned industrial requirements.

The IP-based hierarchical industrial network is an advanced network for harsh industrial environments. Its unit domain networks and industrial backbone network are installed on a wireless network to support scalability and mobility. An IP address is allocated to every device and system to provide end-to-end communication between devices across different kinds of networks.

The remainder of this paper is organized as follows. In section 2, we review current technologies

* **Received data:** 2011-11-29
Foundation item: MKE (the Ministry of Knowledge Economy), Korea, under the Convergence-ITRC support program (NIPA-2011 C6150-1101-0004) supervised by the NIPA(National IT Industry Promotion Agency); KCC (Korea Communications Commission), Korea, under the R & D program supervised by the KCA (Korea Communications Agency) (KCA-2011-08913-05001)
Corresponding author: Younghan Kim (younghak@ssu.ac.kr)

and standards for industrial wireless sensor networks and propose an architecture for a factory network that borrows from these technologies. We then verify the proposed network architecture with an actual implementation on the simple testbed in section 3. In section 4, we conclude this paper.

1 Evolution of industrial networks

To achieve scalability, flexibility and integration, an industrial network must be developed from a heterogeneous network in which cabling and radio frequency (RF) are mixed into a homogeneous network that runs through wireless technology and IP. To integrate these networks, we recommend constructing an IP-based hierarchical wireless network with wireless mesh network/mobile ad-hoc network (WMN/MANET) technology and allocating an IP address to every device and system.

The research of WMN technology based on IEEE 802.11a/b/g , It is advanced and successfully operated in real fields. These technologies can shift a plant backbone network and some types of unit domain networks to a wireless mesh network[4-6].

In the area of wireless sensor network technology, the standards for ISA100.11a and Wireless HART have already been completed, and the 6LoWPAN is still in the process of standardization.

1.1 Technologies for industrial wireless sensor network

A fieldbus shifts an industrial network from a centralized control system to a distributed control system. Recently, engineers have been devoting significant attention to a wireless fieldbus that uses RF technologies.

ISA100.11a and wireless HART are typical industrial wireless sensor network technologies. These two technologies have similar features[7,8].

1) RF

IEEE802.15.4 is applied as a physical layer and it uses a radio frequency band of 2.4 GHz because this frequency is standard radio frequency band for industry science medical (ISM). Therefore, 2.4 GHz can be used without a licence in most countries, but each country will regulate the band's transmission power.

2) Channel hopping

To enhance the network's performance by avoiding interference and as much noise as possible, we use a frequency hopping method based on time division multiple access (TDMA).

In the channel hopping method, the time is divided into time slots. Each slot gets 10 – 14 ms and a unique frequency.

3) Routing

Devices are classified into routing devices or field devices according to their routing abilities. A routing device can forward the data received from a field device to the destination through a path. It is determined by routing methods that are graph routing and source routing. A link layer is responsible for a process of routing. And routing information is updated by the management system.

4) Security

When a new device joins a network and a device communications with a manager, 128-bit advanced encryption standard is used. They provide a secure communication in end-to-end connection and a hop-to-hop connection.

1.2 IPv6 for industrial wireless sensor network

A process of routing in network layer can support communication between heterogeneous networks and interconnection with the Internet. In order to allocate a unique IP address to every device and every system within a large-scale environment, the introduction of IPv6 is required. The 6LoWPAN, routing over lossy and low-power (RoLL) networks and constrained restful enviroment (CoRE) working groups in Internet engineering task force (IETF) are currently completing the standardization for IPv6 in a constrained environment.

1) 6LoWPAN

It is difficult to apply IPv6 to an industrial network, because these networks have many restrictions, such as low power and lossy link. Fortunately, IETF 6LoWPAN working group (WG) has made progress in the standardization for IPv6 in low-power, lossy-networks (LLNs). The node connected to LLNs must have a 6LoWPAN adaptive layer for IPv6.

The 6LoWPAN decreases the overhead of IPv6 in the LLNs by using a compression method for the IPv6 header[9]. A header must be compressed to reduce overhead in packets. In the process of header compression, a duplication part and an unused part are skipped, and the dispatch field informs all devices of these omissions. The maximum transmission unit (MTU) is 1 280 byte over the Ethernet but only 127 byte over IEEE802.15.4. The 6LoWPAN processes the fragmentation in a 6LoWPAN adaptation layer so that the upper layer is not limited by the MTU.

The neighbor discovery protocol (NDP) in IPv6 is suitable for a function of self-configuration and self-organization in large-scale and harsh industrial network are needed. NDP includes a core function that is stateless and that addresses auto-configuration, neighbor resolution and router discovery[10].

Unlike the IPv6 protocol, 6LoWPAN is designed to minimize the multicast packet so that it will not exacerbate the instability and it can broadcast characters across the wireless network. So, 6LoWPAN suppresses the periodic router advertisement (RA) message only when receiving a router solicitation (RS), and a router send a RA. The duplicated address detection process is completed by registering an address to a 6LoWPAN edge router. An address resolution is processed by getting an address from a 6LoWPAN edge router.

2) Routing protocol for LLNs (RPL)

IETF RoLL WG researches the requirements for routing in LLNs and then has progressed standardization for an IPv6 RPL[11,12].

RPL is a 3-layer routing protocol supporting point-to-multi point (P2MP), multi point-to-point (MP2P) and point-to-point (P2P) routing. RPL is designed to consume minimal power and capacities on LLNs. For scalable link-state propagation in LLNs, RPL uses the trickle algorithm[13]. To ensure its own reliability, RPL can maintain the parent and potential multiple parents to change a parent rapidly in an emergency. In order to deal with link variability, RPL selects a path based on dynamic link metrics, as does the estimated number of transmissions (ETX)[14].

RPL creates a destination-oriented directed acyclic graph (DODAG) that creates a path toward the root. DODAG maintains its own operations by sending DODAG information objects (DIOs) periodically. DIOs is regulated by a trickle algorithm to reduce the network load. In order to find a route to multiple destinations, DODAG uses a destination advertisement object (DAO) message. It forwards this message from a destination node to the root in DODAG.

For the sake of security, RPL supports an optional cryptographic mode by using an advanced encryption standard (AES) and by maintaining the integrity of the routing message with RSA signatures.

3) CoAP

CoAP is a resource-oriented application that can be used in a constrained network as a LLNs. CoAP follows representational state transfer (REST) architecture[15]. REST is a simple architecture and can extend a function easily. Using the methods of HTTP POST, GET, PUT and DELETE, various resources can be created, deleted and expressed. Therefore, CoAP is suitable for industrial automation, which requires an application that delivers the information of various! resources. In addition to these benefits, CoAP provides a transparent end-to-end connection between 6LoWPAN and the Internet because it is based on IP and user datagram protocol (UDP). Currently, CoRE WG is working on the standard for the compatibility between HTTP and CoAP for a system in which CoAP is not installed.

As Table 1 shows, there is! little difference between the various wireless technologies used in industrial automation. However, only 6LoWPAN possesses a routing function in the network layer that has the merit to interconnect with the Internet. Given that inter-operations within wireless mesh networks are based on IPv6, 6LoWPAN is suitable. Wireless HART and ISA100.11a can avoid interference with the method of channel hopping. Like the other technologies, 6LoWPAN can apply the method of channel hopping in the media access control (MAC) layer, and it boosts the network's performance.

Table 1 Comparison of wireless technologies used in industrial automation

	WirelessHART	ISA100.11a	6LoWPAN
RF Tech.	IEEE802.15.4	IEEE802.15.4	IEEE802.15.4
Link layer	Ch. Hopping TDMA	Ch. Hopping TDMA	Not specified
Net layer	Extended HART address mesh network	IPv6 with 6LoWPAN mesh network	IPv6 with 6LoWPAN mesh network
App. layer	HART protocol	ISA100.11a Native protocol	CoAP
Security	AES	AES	AES(option)
Routing	L2 layer Graph-routing Source-routing	L2 layer Graph-routing Source-routing	L3 layer Graph-routing Source-routing

1.3 Proposed hierarchical wireless network architecture

Fig. 1 shows the proposed industrial network architecture.

Every unit domain has a heterogeneous network architecture that adheres to its requirements. Each unit domain includes units for processing sensor and actuator devices, for monitoring and controlling systems and for asset management. They connect to a plant backbone network that supports connection with the Internet, 3G and interconnectivity among unit domains.

In the proposed network, wireless mesh routers form a wireless mesh network based on ad-hoc routing capabilities. Some mesh routers play the role of the edge router in unit domain network, which has not only an interface for connectivity with the external network but also an interface for connectivity with unit domains. Mesh routers have interfaces for 802.11a/b/g working ad-hoc routing protocols to make the plant's wireless mesh backbone network. A network layer on a mesh router has a IPv4/IPv6 dual stack. Some mesh routers serve as a gateway that has the ability to connect with the Internet as well as a 3G network, such as WiMAX or Wibro.

A mobile device for management is directly connected to a mesh router either on ad-hoc mode or AP mode so that the device can connect to the Internet or to another device within a unit domain.

Devices in a unit domain such as sensors and actuators have IEEE 802.15.4 as a physical layer. To avoid interference, frequency hopping is applied to the link layer. A network layer has a 6LoWPAN adaptive layer, so a unique IP address is allocated to every device. By routing protocol, RPL is involved in supporting communication among devices within a unit network. RPL also supports communication between systems or devices and the Internet or other networks. The wireless sensor network is connected through a 6LoWPAN edge router to a wireless plant backbone network. In the case of a large-scale sensor network, a control sensor network supports connectivity with the wireless plant backbone network.

CoAP can function as an application that gathers the information from the sensor and the controlling sensor. All networks in an industrial environment are organized by IP network so that the remote management system and mobile device can connect to them seamlessly.

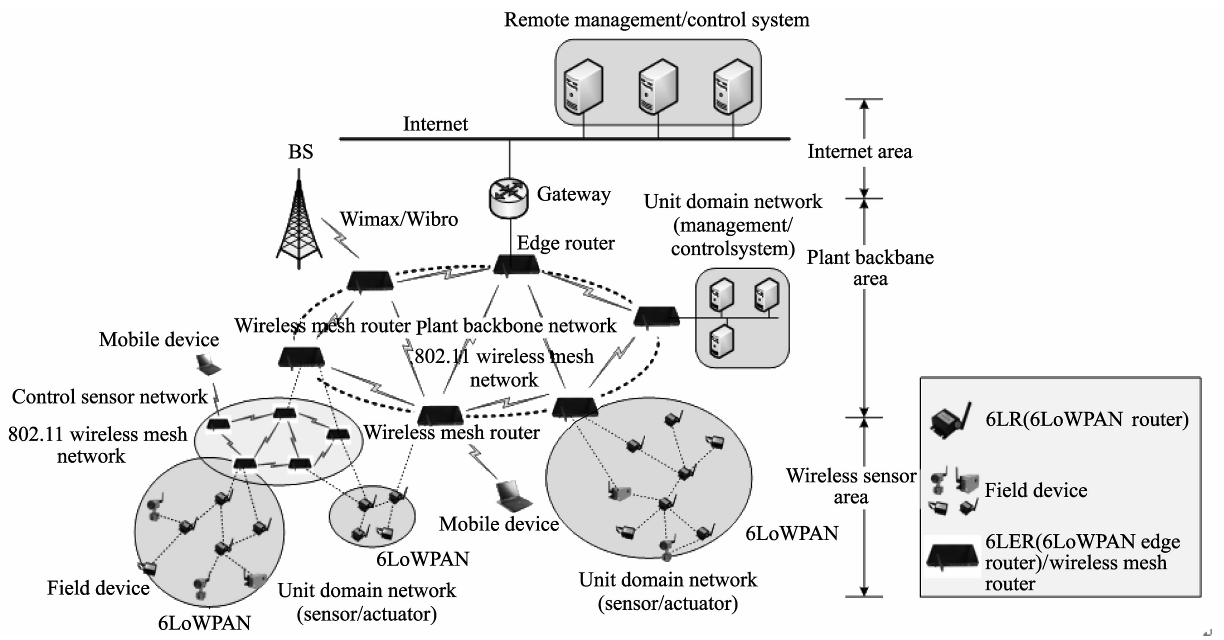

Fig. 1 IP-based hierarchical wireless network for an industrial control system

We illustrate the packet process on the layers of every system in the plant network as shown in Fig. 2.

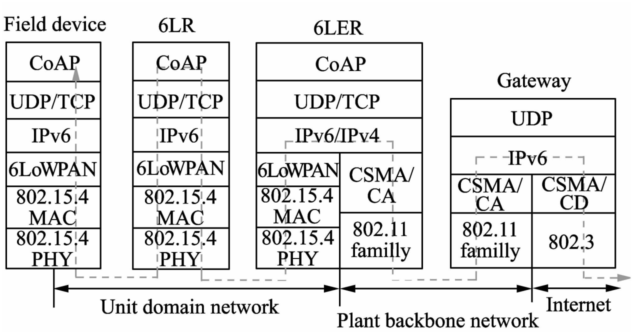

Fig. 2 Protocol layer architecture for an industrial control system

The 6LoWPAN router receives the packet from a field device, and then the 6LoWPAN adaptation layer decompresses the compressed IP header and forwards the larger packet to an IPv6 network layer. The IPv6 searches the forwarding information base (FIB) in the routing table to find the next hop for the packet. If there is no next hop, the IPv6 will forward the packet to the default router. The 6LoWPAN edge router, as does a 6LoWPAN router, decompresses the packet and then forwards the packet to an IPv6 network layer. If there is no routing information for the packet's destination, optimized link state routing (OLSR) sends a route request (RREQ) to find a mesh router that has the information to organize the destinations. Receiving the a route reply (RREP), the packet is forwarded to the next hop.

2 Implementation and testing

2.1 Implementation architecture of a mesh router

The purpose of the implementation architecture of a mesh router is to create a test environment. Fig. 3 depicts the structure of functions in a mesh router.

The function block is divided into a user layer, kernel layer and sink node. The user layer has three user interfaces (UI) and the kernel has a WiFi driver for the RF device, an OLSR routing module and a routing information database. Linux kernel and sink node are connected via a USB serial interface. We use RPL and CoAP, for the sink node.

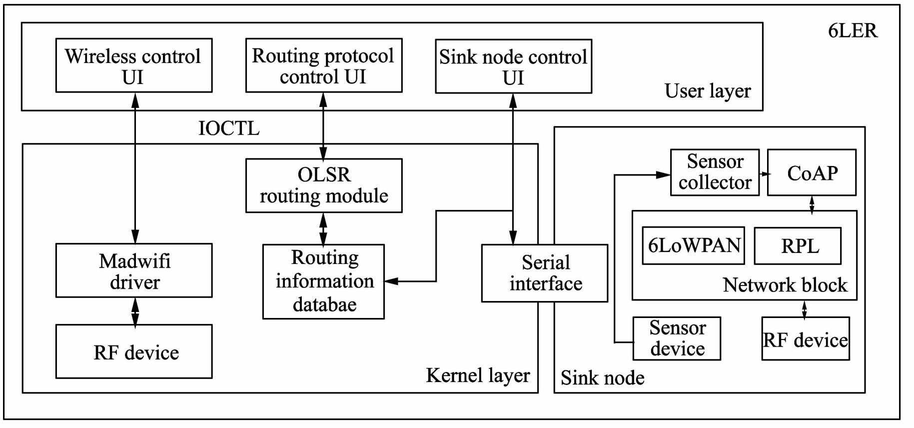

Fig. 3 Mesh router implementation architecture

The UI for wireless control supports wireless function configuration in a similar manner as does an RF channel, tx power and a wireless mode – AP mode or an ad-hoc mode. This wireless control UI delivers the configuration to a WiFi driver in kernel.

The UI for routing protocol control support in order to configure parameters for ad-hoc routing protocols. We implement OLSR as a reactive routing protocol[16]. It is loaded into kernel as one of the modules. We can allocate an IPv6 address to a wireless interface manually via the UI. The UI for sink node control can set a wireless sensor network prefix. At this time, the prefix information is copied to the routing information database so that a packet for a sensor in a wireless sensor network, which was received on a wireless interface, can be forwarded to the wireless sensor network through the serial interface.

2.2 Testing and verification

To test the validation of the proposed IP-based hierarchical wireless network, we implemented field devices, routing devices and mesh routers. We also programmed the CoAP browser and monitor server program. The following table lists the component specifications.

A mesh router constitutes a wireless mesh network. A mesh router equips two wireless interfaces: 802.11b and 802.11a. The 802.11a interface is used for communicating with a mobile device in AP mode. The 802.11b interface, which is operated in ad-hoc mode, supports wireless mesh networking with another mesh router. To configure a wireless mesh network efficiently, we use the virtual topology coordinator (VTC), because this coordinator supports the connection and disconnection between mesh routers via configuration[17].

Table 2 Component specifications

Wireless mesh router Interface: 802.11 a/b/g, USB (connected to sink module) OS: Linux with IPv6 module
Sensor device RF transceiver: 2.4 GHz IEEE 802.15.4 Sensor module: temperature, humidity, illumination
Monitoring server OS: Windows XP Management program: monitoring and control tools including CoAP application based on Java program
Mobile device Portable device using based on Windows XP

To connect the network with Wibro, one of mesh routers connects a Wibro dongle on an USB port. Another mesh router, which plays a role of a 6LoWPAN edge router in the 6LoWPAN network, has a sink device on a USB port.

During our implementation of the mesh routing protocol modules, we used OLSR as a proactive routing protocol as a part of the kernel modules. The prefix information for the wireless sensor network is statically inserted into the routing table.

Fig. 4 illustrate the implemented network. First, a monitoring server connected to wired network sends a GET method to a sensor node to discover information which is available in each sensor node. Because the sensor node has a Wibro dongle, the node then forwards the message to the gateway through the Wibro network by using a femtocell, and then the gateway forwards the message to the gateway that is connected to the wireless sensor network. The gateway finally sends it to a sensor through the sink device. After the monitoring server finds out the kind of information that the sensor supports, it requests and retrieves that information frequently.

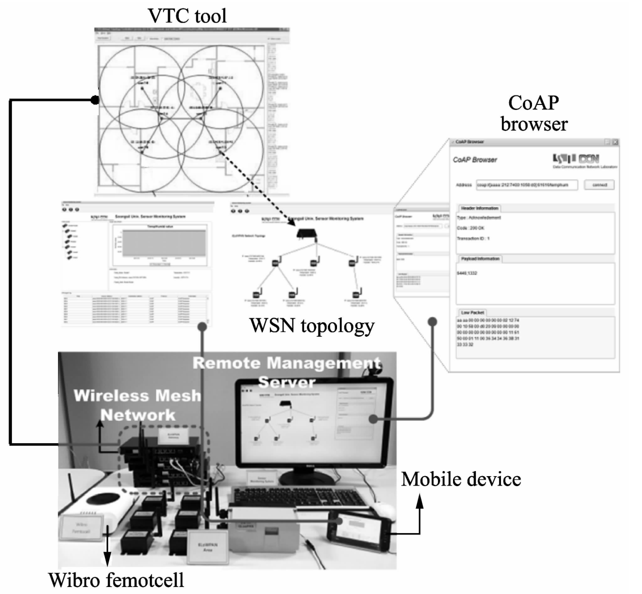

Fig. 4 Implementation and test environment

In the case of a mobile device, it attaches the wireless mesh router and sets an IPv6 address through a process of auto-configuration. After that, the mobile device acquires information about the sensor and then gets data from the sensor in the same manner as the monitoring server does.

3 Conclusion

In order to meet the requirements for an industrial network, a wireless network technology must be applied to every network within a given industrial environment, from unit domain networks to the plant backbone network. Furthermore, the end-to-end communication must be supported by IP.

In this paper, we proposed an IP-based hierarchical wireless network architecture and applied some of the technologies of 6LoWPAN to the architecture. Finally, through a real implementation, we verified our proposed architecture.

References

[1] Gungor V C, Hancke G P. Industrial wireless sensor networks: challenges, design principle, and technical approaches. IEEE Trans. on Industrial Electronics, 2009, 56(10):4258-4265.

[2] Willing A. Recent and emerging topics in wireless industrial communications: a selection. IEEE Trans. on Industrial Informatics, 2008, 4(2):102-124.

[3] Garcia J, Palomo F R, Luque, et al. Reconfigurable distributed network control system for industrial plant automation. IEEE Trans. on Industrial Electronics, 2004, 51 (6):1168-1180.

[4] Esmailpour A, Nasser N. Topological-based architecture for wireless mesh networks. IEEE Trans. on Wireless Communications, 2011, 18(1):74-81.

[5] Bicket J, Biswas S, Aguayo D, et al. Architecture and evaluation of the MIT roofnet mesh network. Proc. of the 11th Auunal International Conference on Mobile Computing and Networking (MobiCom'05), 2005.

[6] Yick J, Mukherjee B, Ghosal D. Wireless sensor network survey. Computer Networks, 2008, 52(12):2292-2330.

[7] Song J P, Han S, Mok A K, et al. Wireless HART: applying wireless technology in real time industrial process control. Proc. of IEEE Real-time and Embedded Technology and Applications Symposium (RTAS'08), St. Louis, USA, 2008:377-386.

[8] ISA100.11a. ISA. Draft2b Wirless System for Industrial Automation: Process Control and Related Applications, 2009.

[9] Hui J, Ed, Thubert P. Compression format for IPv6 datagrams in low power and lossy networks (6LoWPAN). Draft-ietf-6lowpan-hc-15, IETF draft, 2011.

[10] Shelby Z, Chakrabarti S, Nordmark E. Neighbor discovery optimization for low-power and lossy networks. Draft-ietf-6lowpan-nd-15, IETF draft, 2010.

[11] Pister K, Thubert P, Dwars S, et al. Industrial routing requirement in low-power and lossy networks. RFC5673, IETF RFC, 2009.

[12] Winter T, Thubert P, Brandt A, et al. RPL: IPv6 routing protocol for low power and lossy networks. Draft-ietf-roll-rpl-19, IETF draft, 2011.

[13] Levis P, Clausen T, Hui J, et al. The Trickle algorithm. RFC6206, IETF RFC, 2011.

[14] Douglas S J, Aguayo D, Bicket J, et al. A high-throughput path metric for multi-hop wireless routing. Proc. of the 9th Annual International Conference on Mobile Computing and Networking, San Diego, CA, USA, 2003.

[15] Shelby Z, Hartke K, Bormann C, et al. Constrained application protocol (CoAP), Draft-ietf-core-coap-06, IETF draft, 2011.

[16] Clausen T, Jacquet P, Adjih C, et al. OLSR: optimized link state routing protocol. RFC 3626, IETF RFC, 2003.

[17] Kan N, Kan S,. Lee Y, et al. Design and implementation of protocol evaluator for ubiquitous community network. Proc. of UbiComp 2007, Innsbruck, Austria, 2007.