Network synchronization scheme for scalable two-way multi-hop network employing MIMO network coding

Yutaro Kida[1], Keiichi Mizutani[1], Gia Khanh Tran[1], Takehiro Miyamoto[2], Kei Sakaguchi[1], Kiyomichi Araki[1]
[1]Tokyo Institute of Technology, Ookayama 2-12-1, Meguro, Tokyo, 152-8552, Japan
[2]Nihon Dengyo Kosaku Co., Ltd., Nissai-Hanamizuki 7-4, Sakado, Saitama, 350-0269, Japan
{kida, mizutani, khanhtg, sakaguchi, araki}@mobile.ee.titech.ac.jp, miyamoto-takehiro@den-gyo.com

***Abstract*—In recent years, wireless mesh network functioning as backbone for various sensor network applications has been attracting much of attention. For realization of a high data rate and reliable mesh network, a synchronized mesh network technology employing OFDM has been proposed. However, the conventional scheme is not convenient as it requires network synchronization of all the nodes in the network performed before starting data communication. This paper proposes a novel scalable network synchronization scheme where data transmission and network synchronization setup can be done simultaneously. The proposed algorithm is implemented in developed 950 MHz TDD MIMO two-way relay network prototype hardware, and its behavior is verified.**

I. Introduction

In recent years, wireless multi-hop relay technology, in which multiple nodes are connected through wireless links, has been attracting much attention of researchers, owing to the low power transmission and robustness. In this network, nodes cooperate for data transmission through multi-hop, and form the so-called wireless multi-hop network. Wireless multi-hop network has become more attractive as there are more demands for its applications, namely wireless sensor networks, and smart utility networks [1]. However, due to a large range of its applications, future wireless multi-hop network need to support both high data rate and high reliability.

Conventional wireless multi-hop network [2] utilizes carrier sense multiple access with collision avoidance (CSMA/CA) [3]. Futhermore, for the purpose of improving transmission efficiency, synchronized schemes such as slotted ALOHA [4] and slotted CSMA/CA [5] have also been proposed. However, these CSMA/CA based protocols can not achieve high data rate because of many problems including hidden and exposed terminal problems [6].

For realizing high data rate wireless multi-hop network, TDD/TDMA based two-way multi-hop networks have been studied. In this network, forward and backward streams are transmitted at the same time. Especially, high rate wireless multi-hop network is achieved by the combination of MIMO technology [7] together with network coding [8], [9], [10] or beamforming [11]. Furthermore, MIMO multiple access and orthogonal frequency division multiplexing (OFDM) are adopted for two-way multi-hop network to achieve higher frequency efficiency, and robustness against frequency selective fading.

However, when a block processing such as OFDM is combined to multiple access system, all multiple access signals must arrive at the receiver simultaneously. Because the arrival time mismatch between the multiple access signals causes frame synchronization error of the block processing, inter-symbol interference (ISI) and inter-carrier interference (ICI) occur. To avoid such interferences, each node needs to adjust its own transmission timing. How the nodes adjust their transmission timing to achieve multiple access synchronization is called network synchronization scheme in this paper. A MAC layer relative synchronization scheme is proposed in [12], [13]. FTSP [12] achieves timing synchronization with high precision for single-hop, but the performance is not scalable for multi-hop networks. A PHY layer network synchronization scheme has been proposed as an extension of the ranging scheme [14] of OFDMA in the two-way multi-hop networks [15]. However, due to the simplicity of the conventional scheme, there is still spaces for improvement. Thus, we propose the node extention typed network synchronization scheme. In the proposed scheme, a node which tries to join the two-way multi-hop network (new entry node) monitors the communication of this network. The new entry node transmits a control message (new entry message) to the network at the temporary transmission timing. When the proposed scheme is used, the new entry node establishes network synchronization without communication impairment, and time efficiency of network synchronization is improved because network synchronization and data communication can be performed simultaneously. In this paper, node extention typed network synchronization scheme is implemented in hardwares for 950MHz band low-power wireless system to verify the proposed scheme in practical environment. A verification shows the effectiveness of the proposed algorithm.

The rest of the paper is organized as follows. Sect. 2 describes MIMO two-way multi-hop network employing MIMO network coding. Details about the conventional and the proposed network synchronization scheme are provided in Sect. 3. Sect. 4 describes the behavior of the proposed network synchronization scheme using the prototype hardwares. Finally, the paper is concluded in Sect. 5.

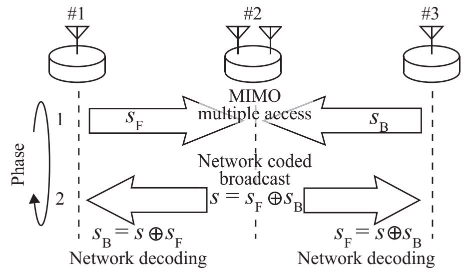

Fig. 1. Two-way multi-hop network utilizing MIMO network coding.

II. MIMO Two-way Multi-hop network using network coding

When two-way multi-hop network is employed as backbone network, high network traffic is assumed for both inbound and outbound communications. Two-way multi-hop network is required to have higher capacity in both directions. By the way, in recent years, MIMO network coding which combines MIMO and network coding is attractive since it allows efficient data transmission. An example is given in Fig. 1. At the 1st time slot, node 1 and 3 transmit the forward packet s_{F} and backward packet s_{B} to node 2 respectively. The relay node 2 receives these two packets using MIMO multiple access at the same time. In the 2nd time slot, node 2 broadcasts the network coded packet s in which the s_{F}, s_{B} are combined,

$$s = s_{\mathrm{F}} \oplus s_{\mathrm{B}}, \tag{1}$$

where $\oplus$ denotes the exclusive OR (XOR) operator. The desired signals at node 1 and 3 are s_{B} and s_{F}, respectively. Since node 1 and 3 correspondingly know the packet s_{F} and s_{B}, these nodes can perform network decoding and obtain the desired signal by calculation of XOR with respect to the received packet s.

$$s_{\mathrm{B}} = s \oplus s_{\mathrm{F}} \tag{2}$$

$$s_{\mathrm{F}} = s \oplus s_{\mathrm{B}}. \tag{3}$$

MIMO network coding allows that node 1 transmit the forward packet to node 3, and node 3 transmits the backward packet to node 1 within only two time slots.

III. Network synchronization scheme for TDD multi-hop network

A. Conventional network synchronization scheme

A network synchronization scheme using ranging scheme of OFDMA was proposed in [15]. In this section, we summarize the conventional work. In this network synchronization scheme, each node establishes network synchronization by transmitting preamble signal. Each node synchronizes to the previous hop node. The procedure of this network synchronization scheme is shown in Fig. 2, where node 1 is a source node of forward packet and destination of backward packet, node 3 is a destination of forward packet and source of backward packet. It is expressed as source/destination node, destination/source node in this paper respectively.

(1-1) Node 1 is a master node. The master node fixes its transmission and reception timing, and the interval T. Node 1 transmits a training signal to node 2 at its fixed Tx timing. Node 2 sets the arrival timing of the training signal as its reception timing.

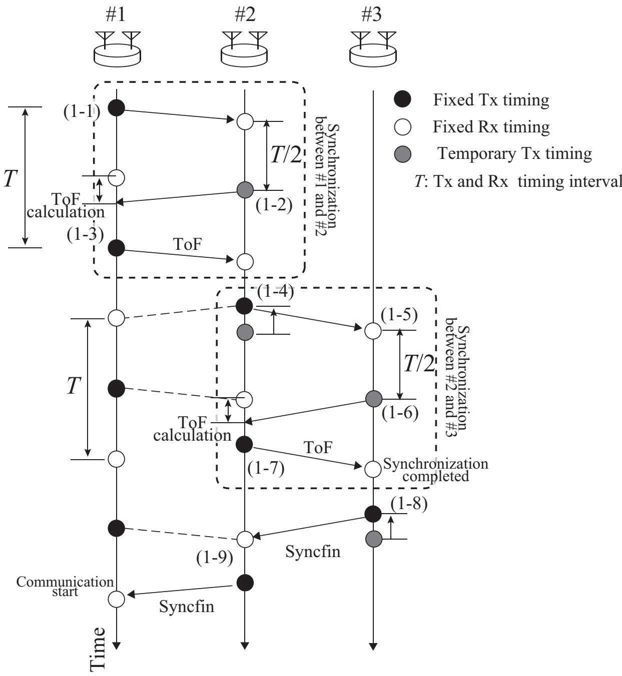

Fig. 2. Conventional network synchronization scheme.

(1-2) Node 2 generates a temporary transmission timing $T/2$ after the fixed reception timing, and a training signal is transmitted to node 1. Node 1 measures the timing mismatch between the arrival time of the training signal and the fixed reception timing of node 1, and calculates the corresponding time of flight (ToF).

(1-3) At the fixed transmission timing of node 1, it transmits the measured transmission timing mismatch ToF to node 2.

(1-4) Node 2 adjusts the temporary transmission timing according to the ToF and sets the timing as its new transmission timing. (1-4) completes the network synchronization between node 1 and 2.

(1-5) Node 2 transmits a training signal to node 3 at its fixed transmission timing in (1-4). Node 3 sets the arrival timing of the training signal as its reception timing.

(1-6) Node 3 generates a temporary transmission timing $T/2$ after the fixed reception timing, and a training signal is transmitted to node 2. Node 2 measures the timing mismatch ToF between the arrival time of the training signal and the fixed reception timing of node 2.

(1-7) At the fixed transmission timing of node 2, the node transmits the measured transmission timing mismatch ToF to node 3.

(1-8) Node 3 adjusts the temporary transmission timing according to the ToF and sets it as the new transmission timing. (1-8) completes the network synchronization between node 2 and node 3.

(1-9) At the fixed transmission timing of node 3, the node transmits a message (Syncfin) to inform the completion of

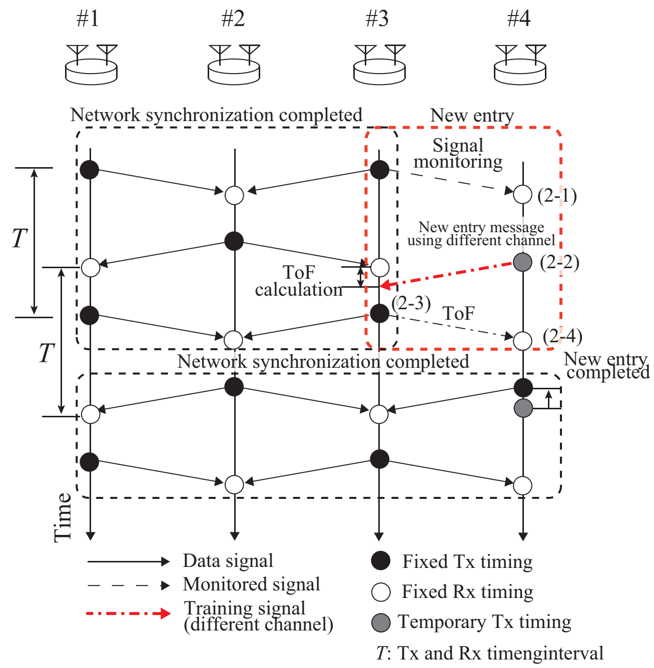

Fig. 3. Node extension typed network synchronization scheme.

network synchronization to node 2. Node 2 then transmits Syncfin to node 1. After that all of the nodes acknowledge about the completion of network synchronization, and start to communicate.

Now, as node 3 transmit at the adjusted transmission timing, the signals transmitted from node 1 and node 3 arrive at node 2 at the same time.

B. Node extension typed network synchronization scheme

In this subsection, we propose a node extension typed network synchronization scheme for the two-way multi-hop network. In the proposed scheme, a node which tries to join this network monitors the communication of the network, fixes its own reception timing and generates a temporary transmission timing. In order to inform about the entry, the node transmits a control message to the network at the temporary transmission timing.

Node extended typed network synchronization for a data transmission on-going network is presented in Fig. 3, where TDD data communication is on-going between node 1, 2, and 3. This figure shows the case that the number of nodes in the network is extended from 3 to 4.

(2-1) Node 4 monitors the communication of the end node (node 3) of the two-way multi-hop network, and fixes the arrival timing of the monitored signal as its reception timing.

(2-2) Node 4 generates a temporary transmission timing $T/2$ after the fixed reception timing, and a training signal is transmitted to node 3. In this transmission, based on its detected transmission channel of node 3, node 4 uses a different channel (new entry channel) to avoid interference with data signal from node 2. Node 3 measures the timing mismatch between the arrival time of the training signal, and calculates the ToF between node 3 and 4.

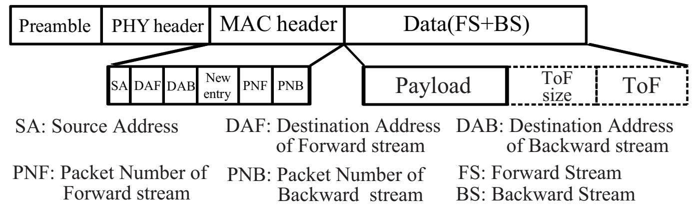

Fig. 4. Frame configuration.

(2-3) Node 3 transmits its backward data to node 2 at its fixed transmission timing. At the same time, node 3 transmits the calculated ToF to node 4 by attaching the information to its transmission data.

(2-4) Node 4 reads ToF from the packet header transmitted by node 3. Same as (1-4), node 4 fixes its own transmission timing based on the received ToF. The network synchronization of node 4 is completed.

This network synchronization scheme can be extended for any number of nodes. This node extension typed network synchronization scheme can even be applied in the initial network synchronization of Fig. 2. Using the scheme, data communication and network synchronization establishment are realized simultaneously. Thus, the efficiency of time slot in the initial network synchronization can be improved. The merits of the proposed scheme are the two following points. First, the new entry node can synchronize autonomously and join the two-way multi-hop network. Second, the new entry node temporarily transmits the new entry signal using new entry channel. The new entry channel is different from data channel. Therefore, the new entry node can establish the network synchronization without affecting data communication. For example, in subsection A (1-4), after network synchronization between node 1 and 2 is established, communication between node 1 and 2 is performed at the same time with the network synchronization between node 2 and 3.

Frame configuration in node extension typed network synchronization scheme is presented in Fig. 4. Signal frame consists of preamble, PHY header, MAC header, and Data. The preamble is used for frame synchronization and channel estimation. The PHY header consists of the modulation scheme, code rate, and the length of the payload. The MAC header consists of the Transmitter Address (TA), Destination Address of Backward stream (DAB), Destination Address of Forward stream (DAF), an information bit for node entry (New entry), Packet Number of Forward stream (PNF), and Packet Number of Backward stream (PNB). The data consists of payload, ToF size, and ToF. ToF size and ToF are utilized only when node extension typed synchronization scheme is used to acknowledge about the ToF to new entry node.

The efficiency of the proposed scheme is shown in Fig.5. The figure shows the required time slots for network synchronization when a new node joins the network using the conventional and the proposed scheme. The horizontal axis shows the total number of nodes including the new entry node, and the vertical axis shows the number of required time slots for network synchronization after the entry of the new node. The number of required time slots are the same for any entry

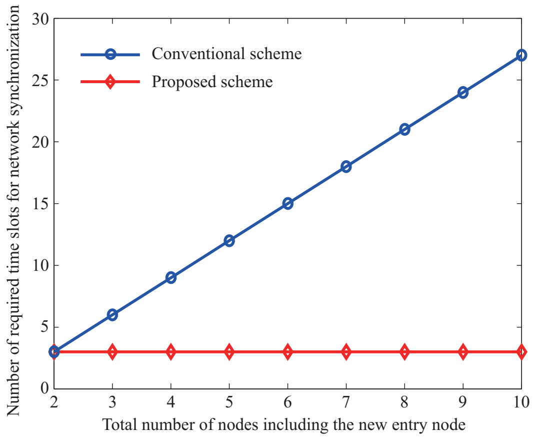

Fig. 5. Number of required time slots for new node entry.

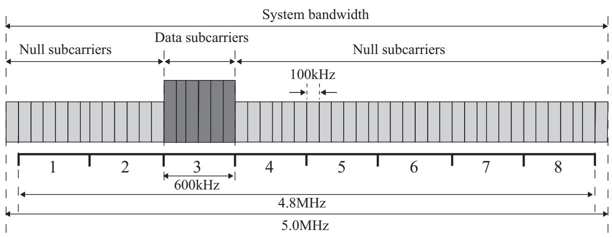

Fig. 6. OFDM signal format.

of a new node regardless of the network size. In other words, the proposed scheme is scalable and the required time slots for new network synchronization establishment is independent with respect to the network size. By contrast, in the conventional network synchronization scheme, the required time slots are increased as the size of the network increases. It is because the conventional scheme is impossible to accommodate a new entry node. Thus, if a new node joins the network, the network needs to perform network synchronization from the starting point.

IV. Experiment Result

A. 950MHz band active low-power wireless system and OFDM signal format

Japanese 950MHz band active low-power wireless system is a spectrum sharing band with RFID. In this system, the channel is defined as shown in Fig. 6. The total number of channel is 8, and the bandwidth per a channel is 600kHz. In this demonstration system, OFDM is employed for the purpose of tolerance against time dispersive multi-path fading. The transmit signal is mapped only to desired subcarriers, while the other subcarriers are null subcarriers. Figure 6 shows the case that the transmit signal is mapped to the third channel.

B. An example of two-way data communication

The experiment environment is showed in Fig. 7. In this system, we use four prototype hardwares to verify the proposed scheme. Node 1 is a source/destination node, node 4 is a destination/source node. Node 2 and node 3 are relay nodes. Each node is equipped with four antennas. However, in this demonstration, when a node transmits a packet, it uses only one antenna, and when a node receives a packet, it uses two antennas for MIMO multiple access. To simplify the experiment, all nodes share a same 10MHz clock (clocks of node 2, 3, and 4 are synchronized to the clock of node 1). The node extension typed network synchronization scheme is implemented in the prototype hardwares.

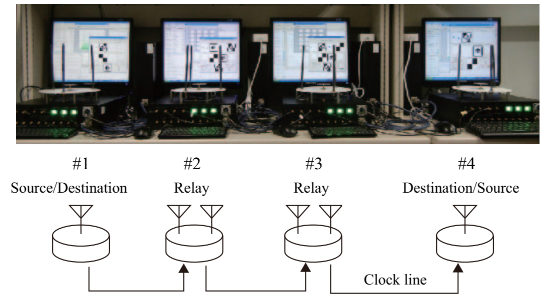

Fig. 7. Demonstration system.

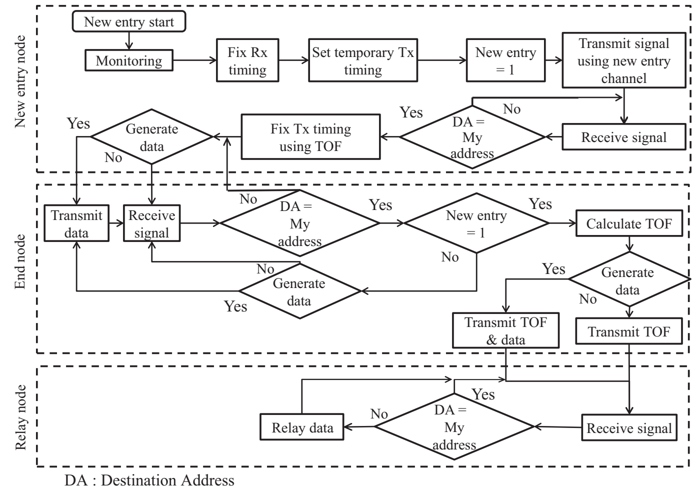

Fig. 8. Flow chart of node extended typed synchronization scheme.

The flow chart of the proposed scheme is shown in Fig.8. Let node i the current end node of the network. Node i has another new entry node i+1 attempting to join the network. Since node i+1 has not already established network sychronization, it monitors surrounding data communication, in this case, from node i. Based on the signal received, node i+1 fixes its reception timing, and generates a temporary transmission timing. Then, the node starts to transmit signal using the new entry channel where the new entry flag is set to 1. Node i accepts the control signal from node i+1, while receiving data of the two-way multihop network from node i-1. It calculates the ToF and feeds back to node i+1. Node i+1 adjusts the transmission timing using the ToF and becomes an end node. On the other hand, node i becomes a relay node. After that, node i+1 generates data and transmits the data to node i. If an end node receives a signal with a valid new entry flag bit 1, the node calculates the ToF, then attaches the ToF to its data and transmits the ToF and data simultaneously. Then it becomes a relay node. When a relay node receives data, it relays data for both forward and backward directions in the next time slot.

In this experiment, when a node completes the network synchronization, it starts communication. An example of a new entry node joining to the two-way multi-hop network is

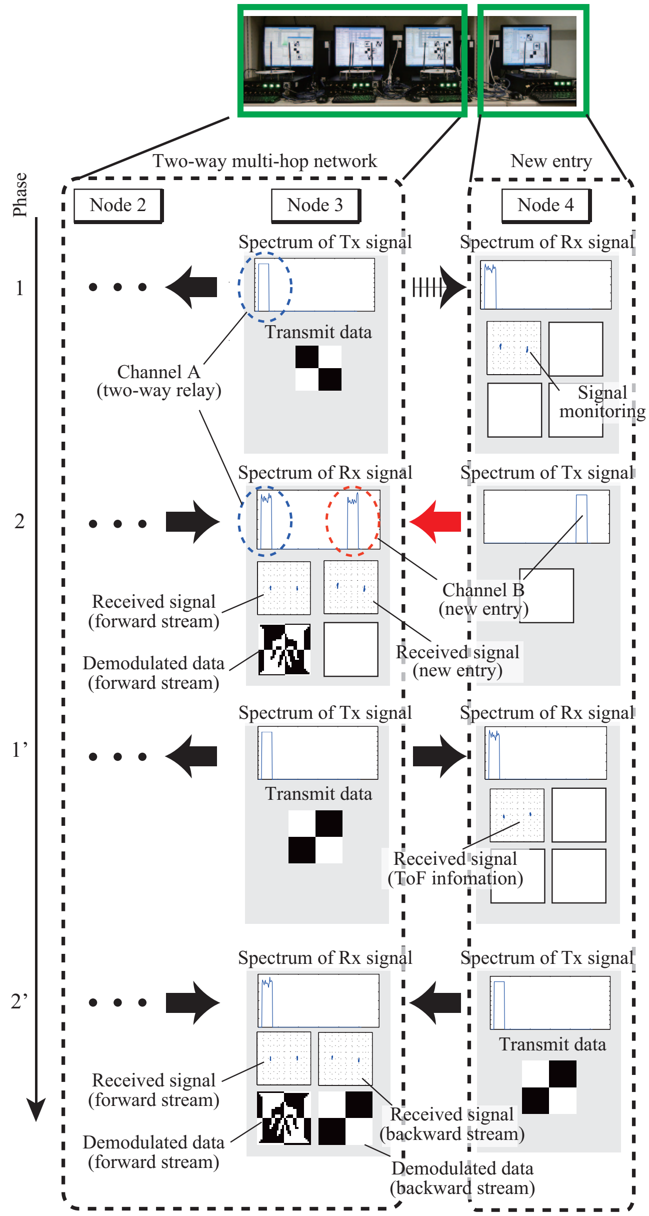

Fig. 9. Snapshot of demonstration.

presented in Fig. 9. In phase 1, the node 1, 2, and 3 have already established the two-way multi-hop network as shown in Fig. 1, thus node 1 is a source/destination node, node 2 is a relay node, and node 3 is a destination/source node. Node 1 transmits the swallow graphic as a forward packet to the relay node, and node 3 transmits the plaid graphic as a backward packet to the relay node. Relay node 2 combines these packets using network coding. These two-way multi-hop are communicated using channel A. Node 4 is a new entry node, so that the node starts the network synchronization by monitoring the communication of the two-way multi-hop network. Node 4 fixes its own reception timing from the arrival time of the monitored signal. In phase 2, node 4 transmits a new entry message to node 3 using new entry channel (channel B). Node 3 receives signal of forward stream and new entry signal, simultaneously. In phase 1', node 3 transmits a backward packet to node 2 and ToF to node 4 at the same time. Finally, phase 2' completes the synchronization of nodes and continues a two-way multi-hop network consisting of 4 nodes. Here, node 4 is a destination/source node, node 3 is a relay node. Using the prototype hardwares, the behavior of the proposed scheme is comfirmed.

V. Conclusion

In this paper, a network synchronization scheme for scalable two-way multi-hop network employing MIMO network coding was proposed. The proposed network synchronization scheme was demonstrated by using the prototype hardwares in developed 950 MHz band for active low-power wireless system. The proposed scheme establishes network synchronization using a temporary channel which is different from the communication channel of the network. Therefore a node can establish the synchronization without stopping communication of the network. It realizes data communication and network synchronization simultaneously, so it is possible to reduce the required time for synchronization establishment in a multi-hop network.

References

[1] P. W. Ragil, G.K. Tran, K. Sakaguchi, “Wireless Grid: Enabling Ubiquitous Sensor Networks with Wireless Energy Supply,” Procs. of IEEE VTC2010 Spring, vo.73 ,pp. 1-5, May. 2011.

[2] I. F. Akyildiz, and X. Wang, “A Survey on wireless mesh networks,” IEEE Commun. Mag., vol. 43, no. 9, pp. 523-530, Sep., 2005.

[3] P. T. Davis, and C. R. Mcguffin, “Wireless Local Area Networks,” McGraw-Hill, pp. 85-115, 1994.

[4] L. G. Roberts, “ALOHA packet system with and without slots and capture,” Comput. Commun. Rev., vol. 5, pp. 28-42, Apr. 1975.

[5] W. Yue, Y. Matsumoto, “Analysis of Wireless LAN Systems with Slotted CSMA/CA Protocol,” Tech. Report, RCS99-88, pp. 7-14, Aug, 1999.

[6] G. K. Tran, K. Sakaguchi, and K. Araki, “MIMO Network Coding-Based PHY/MAC Protocol for Replacement of CSMA/CA in Efficient Two-Way Multihop Relay Networks,” EURASIP Jour. Wirel. Commun. and Net., vol. 2010, Article ID 476732, 20 pages.

[7] F. Ono, and K. Sakaguchi, “Space time coded MIMO network coding,” IEEE Intl. Workshop Wireless Distributed Networks 2008, Sept. 2008.

[8] R. Ahlswede, N. Cai, S. R. Li, and R. W. Yeung, “Network Information Flow,” IEEE Trans. Info. Theory, vol. 46, pp. 1204-1216, 2000.

[9] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, “XORs in the air: practical wireless network coding,” in Proceedings of the ACM SIGCOMM Conf. on Applications, Tech., Arch., and Protocols for Computer Commun., vol. 36, pp. 243-254, Pisa, Italy, Oct. 2006.

[10] F. Ono, and K. Sakaguchi, “MIMO network coding for high efficiency wireless multi-hop network,” IEICE Technical Report, WBS2007-117, March 2008.

[11] F. Ono, and K. Sakaguchi, “MIMO Spatial Spectrum Sharing for High Efficiency Mesh Networks,” IEICE Trans. Commun., vol. E91-B, no. 1, pp. 62-69, Jan., 2008.

[12] M. Maroti, B. Kusy, G. Simon, A. Ledeczi, “The Flooding Time Synchronization Protocol,” Procs. of the 2nd ACM Conf. on Emb. Net. Sen Sys., Baltimore, Maryland, 2004.

[13] S. Ganeriwal, R. Kumar, M. B. Srivastava, “Timing-sync Protocol for Sensor Networks,” Procs. of the 1st ACM Conf. on Emb. Net. Sen Sys., Los Angeles, California, 2003.

[14] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space-time codes for high data rate wireless communications: performance criterion and code construction,” IEEE Trans. Inform. Theory, vol. 44, no. 2, pp. 744 . 765, March 1998.

[15] K. Mizutani, K. Sakaguchi, and K. Araki, “Network Synchronization for Two-way Multi-hop Relay Networks with Block Modulation,” Procs. of IEEE VTC2010 Spring, pp. 1-5, May, 2010.