Channel Time Allocation and Routing Algorithm for Multi-hop Communications in IEEE 802.15.3 High-Rate WPAN Mesh Networks*

Ssang-Bong Jung, Hyun-Ki Kim, Soon-Bin Yim, and Tae-Jin Lee

School of Information and Communication Engineering,
Sungkyunkwan University, Suwon 440-746, Korea
{jssbong,hyunki,sbyim,tjlee}@ece.skku.ac.kr

Abstract. IEEE 802.15.3 High-rate Wireless Personal Area Networks (WPANs) have been developed to communicate with devices within 10m at high speed. A mesh network made up of a parent piconet and several child piconets can support multi-hop communications. In this paper, we propose an efficient Channel Time Allocation (CTA) method and routing algorithm for multi-hop communications in IEEE 802.15.3 high-rate WPAN mesh networks. The proposed CTA allocation method allows sufficient CTA allocation for the relay PNCs. The proposed routing algorithm is tree-based, and the routing tables of parent PNCs and child PNCs are created by efficient device discovery process to find the shortest paths via parent PNCs or subordinate child PNCs. We evaluate the performance of the proposed algorithms via simulations. The proposed algorithms are shown to extend the communication range by multi-hop exchange of packets and to provide sufficient Channel Time Allocations (CTAs) for parent and child PNCs.

Keywords: IEEE 802.15.3 WPAN, multi-hop, mesh network, routing.

1 Introduction

Recently, a lot of personal devices (DEVs) have emerged, and they are often required to interact wirelessly to make information accessible and to exchange data without physical cables. Wireless Personal Area Networks (WPANs) can interconnect DEVs located around person's comfortable workspace wirelessly. WPAN is a developing communication technology to allow short-range wireless ad-hoc connectivity among portable consumer electronics and communication DEVs. Although Bluetooth has introduced as the first WPAN technology [1], it provides the data rate of about 1Mbps, which is limited in the sense it is hard to support high-rate or real-time multimedia traffic [2].

A new high-rate WPAN standard has been developed by IEEE 802.15.3 task group (TG) [3]. The target applications of the high-rate WPAN can be divided into two categories. The first one is multi-megabyte file transfer such as images and mp3 files. The second one is distribution of real-time video and high-quality audio. IEEE 802.15.3

* This research was supported by the Ministry of Information and Communication, Korea, under the ITRC IITA-2006-(C1090-0603-0046) and by grant No.R01-2006-000-10402-0 from the Basic Research Program Korea Science and Engineering Foundation of Ministry of Science & Technology. Dr. Tae-Jin Lee is the corresponding author.

high-rate WPAN [3] operates in the unlicensed 2.4GHz ISM band, and supports the data rate of up to 55Mbps and ad-hoc mode allowing a number of DEVs to communicate with one another in a piconet. A piconet in IEEE 802.15.3 high-rate WPAN consists of several DEVs and one Piconet Coordinator (PNC). If a DEV needs channel time on a regular basis, it asks the PNC for isochronous channel time. A mesh network can be formed by connecting piconets to extend coverage and communication area. As a result, it enhances network reliability and improves network throughput [4]. A mesh network in IEEE 802.15.3 high-rate WPAN consists of a parent piconet and its child piconets. The child PNC of a child piconet is a member of the parent piconet and it also operates as the PNC in the child piconet. A new child piconet is constructed under an established piconet, and the established piconet then becomes the parent piconet. So a child piconet is dependent on the parent piconet [5] and requires channel time allocation to the parent piconet and is synchronized with the parent piconet's timing.

In the current IEEE 802.15.3 high-rate WPAN specification, efficient routing algorithms for multi-hop mesh networks are not defined and only basic frame structure for the formation of a single channel mesh network is defined. Therefore, in this paper, we propose an efficient WPAN mesh network routing algorithm, Parent PNCs and Child PNCs, for multi-hop communications and evaluate its performance. Our proposed mesh network routing algorithm is a tree-based routing algorithm. The routing tables of parent PNCs and child PNCs are created by efficient device discovery process to find the shortest paths via parent PNCs or subordinate child PNCs. And, we also propose CTA allocation mechanism for time division of superframes. We analyze device discovery time and conduct simulations to evaluate its performance. Simulation results validate the desired features of the proposed routing algorithms for multi-hop communications.

The rest of the paper is organized as follows. Section 2 gives an overview of the IEEE 802.15.3 high-rate WPAN Media Access Control (MAC) and mesh networks. In Section 3, we describe our proposed channel time allocation and routing for WPAN mesh networks. Section 4 provides the performance analysis of the proposed algorithm for multi-hop communications. Finally, Section 5 concludes the paper.

2 IEEE 802.15.3 High-Rate WPAN MAC and Mesh Network

An IEEE 802.15.3 piconet consists of a PNC and more than one DEV. A piconet is managed by the PNC, and supports ad-hoc peer-to-peer connection. The PNC provides the basic timing for the piconet with beacons and it allows independent DEVs to communicate one another. The channel time allocation for data transmission in a piconet is given in the superframes. Each superframe begins with a beacon, and Contention Access Period (CAP), and Channel Time Allocation Period (CTAP) follow. The beacon is used to set the timing synchronization and to communicate management information for the piconet, and it is generated and broadcast by the PNC. The CAP is used to exchange association request and response command, channel time request and response command, and asynchronous data. During the CAP, DEVs try to access the channel in a distributed fashion using Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). The CTAP is composed of channel time allocations (CTAs), and management CTAs (MCTAs), which allows TDMA-like medium access.

Fig. 1. Parent piconet and child piconet superframe relationship

IEEE 802.15.3 high-rate WPAN allows a DEV of a piconet to request the formation of a subsidiary piconet. The original piconet is referred to as the parent piconet and the subsidiary piconet is referred to as a child or a neighbor piconet [6]. We call a mesh network as a set of piconets consisting of a parent piconet and its child piconets. Fig. 1 illustrates the relationship between the superframe of the parent piconet and that of the child piconet. The None period denotes that there is no peer-to-peer communications during beacon times. The C-P period denotes communications between a child PNC and a DEV of the parent PNC or the PNC of the parent, and the C-C period denotes communications between child piconet DEV and DEV, or child piconet PNC and DEV. A child PNC is a member of the parent piconet and thus it can exchange data with any DEV in the parent piconet. A parent piconet and its child piconets operate under the same frequency channel. A mesh network can be formed for multi-hop communications with the aid of child PNCs and the parent PNC. How to form a WPAN mesh networks [7] and to route packets in the network are some of the most important issues. We focus on efficient routing of WPAN mesh networks.

3 Proposed Channel Time Allocation and Routing for WPAN Mesh Networks

A mesh network made up of a parent piconet and its child piconets incurs multi-hop communications. Therefore, we need efficient CTA allocation method and routing algorithm for multi-hop communications among DEVs. In this section, we present a mechanism for DEV discovery to create routing tables. Then we present our proposed a CTA allocation method and a routing algorithm. We assume that the PNC of a parent piconet and those of child piconets know the information on the DEVs of the parent piconet and the child piconets, respectively.

3.1 Device Discovery to Form Routing Tables

In this section, we present a method to create routing table. Fig. 2 shows a mesh network example with two levels (L) and routing tables of a parent piconet and child piconets. The parent piconet and child piconets use distinct PNIDs. The parent piconet uses PNID 0 when $L = 0$. The number of child piconets when $L = 1$ is two and the child piconets use PNID 1 and 2. The number of child piconets when $L = 2$ are three and the child

piconets use PNID 3, 4, and 5. The parent piconet has to know all the PNIDs of the child piconets and the topology under the PNC to make a routing table. When a child piconet is formed, the PNC of the child piconet informs its member DEV Identifiers (DEVIDs) and PNID to its parent. The PNC that receives the descendents information pass it all the way up to the root parent PNC (PNC with PNID 0), and the PNC then creates the routing table. In this way, a tree-shape PNC hierarchy is constructed (see Fig. 3). Therefore, the root parent piconet can have all the PNIDs. Child piconets only have to know PNIDs of its subordinate child piconets.

Bandwidth allocation for the parent piconet and its child piconets has been present in [7]. To explain the DEV discovery for routing table formation and the CTA allocation for a DEV or PNC, we define the following notations:

- S : Maximum superframe size
- T_B : Beacon time
- T_{CAP} : Channel access period
- T_{CTA} : Channel time allocation
- N_p : Number of DEVs in the parent piconet
- L : Number of levels
- N_{PNID} : Number of PNIDs
- n_i : Number of DEVs in level i , $i = 1, 2, \dots, L$
- m_i : Number of child piconets in level i , $i = 1, 2, \dots, L$
- R_{CTAI}^i : CTA allocation remainder to one piconet in level i , $i = 1, 2, \dots, L$
- T_{Ssize}^i : Available superframe size for level i in mesh network, $i = 1, 2, \dots, L$
- $T_{Discovery}^i$: Device discovery time in level i , $i = 1, 2, \dots, L$
- T_{Csize}^i : Available CTA size of child piconets in level i , $i = 1, 2, \dots, L$
- C_{P-CTA}^0 : Available CTA of parent PNC with PNID 0
- C_{D-CTAI}^j : Available CTA of a DEV with PNID j , $j = 1, 2, \dots, N_{PNID}$
- C_{C-CTA}^j : Available CTA of child PNCs with PNID j , $j = 1, 2, \dots, N_{PNID}$
- Sn_j : Number of source DEVs with PNID j , $j = 0, 1, \dots, N_{PNID}$
- Rn_j : Number of relay PNCs with PNID j , $j = 0, 1, \dots, N_{PNID}$
- B_{CTA}^j : Allocated bandwidth in a piconet with PNID j , $j = 0, 1, \dots, N_{PNID}$
- r : CTA ratio between the parent PNC and its child PNCs
- R_{C-PNC} : Basic CTA ratio between the parent PNC and its child PNCs

We can calculate the available CTA size of child piconets in level i , T_{Csize}^i by Eq. (1). The T_{Csize}^i consists of a beacon time and a CAP, and the basic CTAs for the DEVs. Since m_i child piconets request beacon time, CAPs, and CTA allocation remainder (R_{CTAI}^{i+1}) for child piconets for the next level $i+1$, and, n_i DEVs in level i are assigned T_{CTA} ,

$$T_{Csize}^i = (T_B + T_{CAP} + R_{CTAI}^{i+1}) \times m_i + (T_{CTA} \times n_i), \quad i = 1, 2, \dots, L. \quad (1)$$

The T_{Ssize}^0 consists of a beacon time and a CAP, and the basic CTAs for the parent piconet DEVs and is computed as Eq. (2). We can calculate the available superframe size for level i , T_{Ssize}^i by Eq. (3). The R_{CTAI}^1 is the CTA allocation remainder to one child piconet for level 1.

$$T_{Ssize}^0 = T_B + T_{CAP} + (T_{CTA} \times N_p) \quad (2)$$

Fig. 2. Routing table example of a mesh network

Fig. 3. The tree hierarchy of Fig. 2 example

$$T_{S_size}^i = T_{S_size}^0 + R_{CTAI}^l + \left(\sum_{n=1}^i T_{C_size}^n \right), \quad i = 1, 2, \dots, L. \quad (3)$$

The DEV discovery ($T_{Discovery}^0$) time in level 0 consists of a $T_{S_size}^0$ and a beacon time and is computed by Eq. (4). We can calculate the device discovery time for level i , $T_{Discovery}^i$ as Eq. (5).

$$T_{Discovery}^0 = T_{S_size}^0 + T_B \quad (4)$$

$$T_{Discovery}^i = (T_{S_size}^i \times (i + 1)), \quad i = 1, 2, \dots, L. \quad (5)$$

3.2 Proposed Channel Time Allocation Method and Routing Algorithm

The CTA allocation and routing algorithm have a great effect on efficient data transmission. In this section, we propose an efficient CTA allocation method and a routing algorithm. We assume that parent PNCs and child PNCs can support packet relay. Source DEVs will generate a new packet for data transmission. If the parent PNC or child PNCs receive the packet, they relay the packets. So CTAs of a superframe are allocated to source DEVs and the relaying PNCs. The parent PNC is located at the center of data transmission. Consequently, the traffic of parent PNC often experience heavy traffic. The proposed CTA allocation method allocates sufficient CTAs for the relay of the parent PNC. We can calculate the available CTA of a DEV in piconets with PNID 0, $C_{D_CTAI}^0$ by Eq. (6). The $C_{P_CTAI}^0$ denotes available CTAs of its parent PNC in a parent

PROCEDURE Routing Algorithm in Parent PNC and Child PNCs	
1:	while (a packet is received)
2:	if (there exists the destination PNID in the routing table)
3:	if (the destination PNID of the packet is the same as its own PNID)
4:	Send the packet to the destination DEVs
5:	else
6:	Send the packet to the next hop according to the routing table
7:	else
8:	Forward the packet to the upper PNC

Fig. 4. Pseudocode of the proposed routing algorithm

piconet with PNID 0 and is computed as Eq. (7). The $C_{C_CTA}^0$ is available CTAs for child PNCs with PNID 0,

$$C_{D_CTA}^0 = \frac{B_{CTA}^0}{Sn_0 + (Rn_0 + 1) \times R_{C_PNC} + (2 \times r)}, \quad r = 0, 1, \dots, R_{max} \quad (6)$$

$$C_{P_CTA}^0 = C_{D_CTA}^0 \times (R_{C_PNC} + (2 \times r)), \quad r = 0, 1, \dots, R_{max} \quad (7)$$

$$C_{C_CTA}^0 = C_{D_CTA}^0 \times R_{C_PNC} \quad (8)$$

where R_{max} is the maximum CTA ratio between a parent PNC and its child PNCs, and B_{CTA}^0 is the allocated bandwidth in the parent piconet with PNID 0 and Sn_0 is the number of source DEVs for PNID 0. And, Rn_0 is the number of child piconets for PNID 0. The child PNCs are the member of their parent piconet and R_{C_PNC} is the basic CTA ratio the parent PNC and child PNCs. The R_{C_PNC} value is set to two. The 1 in Rn_0+1 denotes the number of CTAs for the parent piconet and the 2 in $2 \times r$ denotes the number of CTAs for uplink and downlink relay.

We can calculate the available CTA of a DEV in child piconets with PNID j , $C_{D_CTA}^j$ by Eq. (9). The $C_{C_CTA}^j$ presents the available CTAs of child PNCs in child piconets with PNID j and is computed as Eq. (10).

$$C_{D_CTA}^j = \frac{B_{CTA}^j}{Sn_j + (Rn_j + 1) \times R_{C_PNC}}, \quad j = 1, 2, \dots, N_{PNID} \quad (9)$$

$$C_{C_CTA}^j = C_{D_CTA}^j \times R_{C_PNC}, \quad j = 1, 2, \dots, N_{PNID} \quad (10)$$

We then describe the proposed routing algorithm in the parent PNCs and the child PNCs. The proposed routing algorithm is a tree-based routing algorithm as in Fig. 3, which shows the tree hierarchy structure associated with Fig. 2. The routing tables of parent PNCs and child PNCs are created by an efficient device discovery process to find the shortest paths via parent PNCs or subordinate child PNCs as explained in Section 3.1. The pseudocode of the proposed routing algorithm is shown in Fig. 4. While parent PNCs or child PNCs receive a packet, if there exists the PNID of a destination DEV in the routing table, either parent PNC or child PNCs compare the destination PNID with its own PNID. If the destination PNID is the same as its own PNID, the packet is sent to the destination DEV. Otherwise, either parent PNCs or child PNCs send to the next

Table 1. Simulation parameters

Parameter	Value
Number of DEVs	100
Channel bandwidth	55 Mbps
Number of S-D pairs	5 ~ 30
Maximum buffer size	307,200 byte
Packet size	64 ~ 2,032 bytes
Beacon time (T_B)	0.6 ms
CAP time (T_{CAP})	1.00 ms
Maximum Superframe size (S)	65.535 ms
Guard time (T_{GI})	0.0328 ms
SIFS	0.01 ms
MPEG-4 traffic rate	4 Mbps

Fig. 5. End-to-end delay vs. the number of S-D pairs

Fig. 6. Packet loss rate vs. the number of S-D pairs

hop according to the routing table. If there does not exist the destination PNID in the routing table, the packet is forwarded to the upper PNC. Because of the tree hierarchy, a packet is destined to the proper destination DEV by the proposed routing mechanism.

4 Performance Evaluation

We evaluate the performance of the proposed CTA allocation method and the routing algorithm for multi-hop communications via simulations. The simulation parameters are summarized in Table 1. The DEVs are assumed to be located uniformly in a square area of 50m × 50m. The mesh network formation algorithm and the bandwidth allocation for the parent piconet and child piconets are adopted as in [7]. We use MPEG-4 traffic model for isochronous traffic and its data rate of is 4 Mbps. The length of a MAC Service Data Unit (MSDU) is generated uniformly in 64 ~ 2,032 bytes. The 802.15.3 protocol adds Short Interframe Space (SIFS) and guard time between individual CTAs to keep transmissions in adjacent CTAs from colliding.

Fig. 7. Throughput vs. the number of S-D pairs

We analyze the performance of the CTA allocation method and the routing algorithm with respect to end-to-end delay, packet loss, and throughput. Fig. 5 presents the end-to-end delay by the proposed CTA allocation method and the routing algorithm. We compared end-to-end delays under various CTA ratio (r) and the number of source-destination (S-D) pairs. The end-to-end delay is about 0.54 second when $r = 0$ and the number of S-D pairs = 30. The end-to-end delay is improved up to approximately 0.24 second when $r = 3$ and number of S-D pairs = 30. As r increases, the end-to-end delay is shown to be decreased since PNCs are allocated more CTAs for relaying traffic. Fig. 6 presents the packet loss rate of the proposed algorithm. When the number of S-D pairs increases, the packet loss rate increases up to about 3 ~ 5%. We also analyze the total throughput. Fig. 7 shows the throughput performance of the proposed CTA allocation method and the routing algorithm. Total throughput increases as r and the number of S-D pairs increase. When r is 3 and the number of S-D pairs is 30, the total throughput becomes the maximum at about 3.4 Mbps.

5 Conclusion

In this paper, we have proposed the CTA allocation method and routing algorithm for multi-hop communications in IEEE 802.15.3 high-rate WPAN mesh networks. The proposed CTA allocation method allocates sufficient CTAs for relay PNCs. The proposed routing algorithm is simple and tree-based, and the routing tables of parent PNCs and child PNCs are created by an efficient device discovery process to find the shortest paths via parent PNCs or subordinate child PNCs. We evaluate the performance of the proposed algorithms via simulations. The end-to-end delay, the packet loss rate, total throughput indicates desired characteristics. The proposed algorithms are able to provide efficient multi-hop communications in IEEE 802.15.3 WPAN mesh networks.

In the future we intend to include the effects of various CTA allocation schemes for the relay PNCs and DEVs. Further, we are implementing and studying other features of the routing algorithm and bandwidth allocation.

References

1. IEEE, "Standards for Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs)," Jun. 2002.
2. J. Karaoguz, "High-Rate Wireless Personal Area Networks," IEEE Communications Magazine, vol. 39, no. 12, pp. 96-102, Dec. 2001.
3. IEEE, "Standard for Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs)," Sep. 2003.
4. Artimi Company Ltd. UWB and Mesh networks white paper. Avail at <http://www.artimi.com>, Aug. 2003.
5. D. Trezentos, G. Froc, I. Moreau and X. Lagrange, "Algorithms for Ad-hoc Piconet Topology Initialization Evaluation for the IEEE 802.15.3 High Rate WPAN System," in Proc. of IEEE VTC, vol. 5, pp. 3448-3452, Oct. 2003.
6. X. Chen, J. Lu, Z. Zhou, "An enhanced high-rate WPAN MAC for mesh networks with dynamic bandwidth management," in Proc. of IEEE GLOBECOM, vol. 6, pp. 3408-3412, Nov.-Dec. 2005.
7. S.-B. Jung, S.-B. Yim, T.-J. Lee, S.-D. June, H.-S. Lee, T.-G. Kwon, and J.-W. Cho, "Multipiconet Formation to Increase Channel Utilization in IEEE 802.15.3 High-rate WPAN," Springer-Verlag Lecture Notes in Computer Science, vol. 3392, pp. 1041-1049, May 2006.