Thesis for the Degree of Master of Science

ISRMC-MAC : Implementable Single-Radio Multi-Channel MAC Protocol

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by

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Submitted to the Department of Computer Engineering
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Master of Science

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Abstract

WBAN(Wireless Body Area Network) which has received a lot of attention for developing medical and entertainment services is standardized by IEEE 802.15 Task Group 6(TG6). WBAN should be guaranteed low data latency because medical data must be timely and correctly transferred. Since the standard considers only a single-channel, it has problems such as intervention and large latency. To solve these problems, a lot of multi-channel TDMA MAC protocols have been proposed. However, multi-radio multi-channel MAC protocols cannot be implemented on current off-the-shelf sensor modules because they have a single-radio transceiver. Furthermore, existing single-radio MAC protocols duplicate data, which may lead to energy inefficiency. In this paper, we propose a single-radio multi-channel TDMA MAC protocol which can support low data latency, high reliability, and energy efficiency. To achieve above goals, the proposed protocol employs an inventive topology, i.e., star plus mesh topology. In addition, we implement our protocol on real sensor modules, ZigbeX-I and ZigbeX-II based on IEEE 802.15.4 packet frame and superframe so that we can verify the performance in real environment.

Thesis Supervisor: Jinsung Cho

Title: Professor

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Chapter 1

Introduction

Recently, various kinds of medical IT equipments and technologies have been developed because many countries are interested in healthcare due to aging society. WBAN which was standardized by IEEE 802.15 Task Group 6(TG6) [1] in 2012 is one of those technologies. It continuously checks and communicates body conditions. In order to make above environment, WBAN uses tiny sensors which are attached in/out/around human body. Tiny sensors can occupy ISM(2.4GHz) or MICS(402–405MHz) bands. When sensors are implanted in human body, MICS band that is not harmful to body is used instead of ISM band. Usually, battery capacity of sensor is limited because sensor cannot be freely charged when they are moved with human body. Thus, energy efficiency and energy harvesting are important issues in WBAN [2]. In addition, WBAN requires low data latency and high reliability [2], since it can result in poor recognition and prevention when an emergency situation occurs. To overcome these issues, various kinds of MAC protocol have been proposed.

The standard WBAN employs star topology and single channel MAC protocol based on contention. This protocol may lead energy inefficiency and high data latency because many nodes want to concurrently send data to sink node on only one channel with one radio transceiver. To solve these problems, contention-free based MAC protocols using single-radio single-channel TDMA and multi-radio multi-channel TDMA have been proposed recently. Specifically, a number of multi-channel TDMA based MAC protocols have been proposed in WSN(Wireless Sensor Network) area such as COM-MAC [3], T-MALOHA [4], and E2RMAC [5], etc. Most of these protocols are supposed that the sink node which is equipped with multiple radio transceivers, so that they can receive or send data concurrently on multiple channels. Therefore, it can guarantee efficiency of communication. However, these protocols cannot be implemented on current off-the-shelf sensor modules because they have a single-radio transceiver. On the other hand, single-radio multi-channel TDMA MAC protocols based on inventive topology and algorithm are feasible on off-the-shelf sensor modules that all of sensor nodes(include sink node) are equipped with single-radio [6-8]. Unfortunately, however, it cannot guarantee energy efficiency. Almost of these protocols use tree-topology and thus they perform data aggregation process which means that parent node aggregates data from child nodes. It makes data duplication which may increase the total data size.

In this paper, we design and implement a single-radio multi-channel TDMA MAC protocol which can solve the above problems in terms of data latency, energy efficiency, and reliability. We employ a mixture of star and mesh topology which can improve energy efficiency by reducing data redundancy and reduce data latency through the proposed multi-channel algorithm. Finally, we implement the proposed protocol in real sensor modules which are ZigbeX-I and ZigbeeX-II and validate performance through empirical experiments. The performance is compared with HyMAC [9], and MuChMAC [10] which are single-radio multi-channel protocols.

The rest of the paper is organized as follows. Section 2 reviews the most relevant related works, and Section 3 proposes our single-radio multi-channel MAC protocol based on star plus mesh topology and explains the detailed operation. In Section 4, we show the performance evaluation from our prototype implementations. Finally, we conclude the paper in Section 5.

Chapter 2

Related Work

From now on, baseline MAC protocol is same with the star topology based single-radio single-channel TDMA MAC protocol. Baseline MAC protocol has high data latency because many nodes wait their own time slot. To solve these problems, a number of multi-channel MAC protocols are proposed in WBAN and WSN area. These multi-channel MAC protocols can be divided into two categories which are multi-radio and single-radio.

2.1 Multi-Radio Multi-Channel MAC Protocols

A node which has a multi-radio can concurrently communicate with the other nodes using multiple channels. Thus, this method is able to achieve high communication performance, but the node that takes multi-radio consumes more energy rather than other nodes which take single-radio. By considering this shortcoming, almost protocols are proposed that general nodes use single radio while sink node which has powerful transceiver and infinite battery uses the multi-radio.

COM-MAC(Cluster On-demand Multi-channel MAC Protocol) [3] is a multi-channel MAC protocol based on clustering environment. Purposes of this protocol are energy efficiency and high network throughput in WSN. In their work, sensor nodes are organized as three tier architecture. A sink node occupies the top and a relatively small number of aggregators which have the multi-radio and infinite power supplement occupy the middle and a set of sensor nodes occupy the bottom. Aggregator functions as cluster head which schedules the order of sensor nodes in cluster and aggregates data from sensor nodes. Sensor nodes act as cluster member which extracts sensing data and communicates with the aggregator. After that, aggregators send gathered data to the sink node. COM-MAC can ensure high network throughput. But, the assumption that the cluster head has infinite energy is not realistic in WSN.

T-MALOHA(Transmission pipelined Multi-channel ALOHA) [4] is mixture of slotted ALOHA and FDMA. Purposes of this protocol are low data latency and high throughput. Sink node uses multi-radio and other nodes that extract sensing data use single-radio. T-MALOHA divides time into a small frame, and then subdivides it into fixed number of smaller time slots. Each node gets the frame probabilistically. If nodes take the frame, nodes uniformly select time slot to send data. At the end of the frame which is ack-slot, the sink node transmits acknowledgement. If many nodes use same channel and time slot, pipelining scheme is used.

TMCP(Tree-based Multi-Channel Protocol) [11] is a multi-channel MAC protocol based on tree topology. Purposes of this protocol are low data latency and reliability. Sink node uses multi-radio and the other nodes use single radio. This protocol constructs tree topology which utilizes the sink node as a root. The branches which are named as subtree are spread from the sink node and each branch has unique channel. TMCP has three components, CD(Channel Detection), CA(Channel Assignment) and DC(Data Communication). The CD module finds available channels which can be used in current environment. The CA module partitions whole network into k subtrees and assigns unique channel to each subtree. After assigning channels, DC module manages data collection through each subtree. In this protocol, interference can be divided into two categories, one is interference among different subtrees, inter-tree interference and the other is intra-tree interference which indicates interference within a subtree. The unique channel assignment to each subtree can minimize the inter-tree interference, but the intra-tree interference is still serious.

Consequently, these works aim to improve network throughput, energy efficiency and reliability, however, these are not feasible in current off-the-shelf sensor modules since they has only one transceiver.

2.2 Single-Radio Multi-Channel MAC Protocols

Nodes which are equipped with single-radio cannot transmit or receive data concurrently using multiple channels. Furthermore, a node can send or receive data from only one channel by using only one antenna. Thus, it may result in high data latency and channel inefficiency. In order to solve these problems, there are many MAC protocols which use inventive topology and algorithm.

PEDAMACS(Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks) [6] is proposed to guarantee data sending timely and correctly. This protocol assumes that the sink node has striking performances which are powerful transceiver, large storage and infinite battery. The other nodes have a general performance. Excepted the sink node, every nodes use SINR(Signal to Interference plus Noise Ratio) to determine its parent, neighbors and interferers. When the network topology is completely composed, the sink node creates and broadcasts a scheduling message which includes result of time slots allocation. Scheduling message is sent to every node directly because the sink node has striking performances. PEDAMAC reduces intervention and guarantees data communication but, the performance is just validated by computer simulation. No extensional experiment is performed in their work.

HyMAC(Hybrid MAC) [9] is one of multi-channel MAC protocols based on combination of TDMA and FDMA. The network is created based on tree topology. This protocol divides time into fixed size frames and it is subdivided into smaller time slots. These slots are classified as either contention-free or contention period. The scheduling result which generated by sink node is transmitted to other nodes. In the contention period, new nodes are joined or existing nodes send control messages. In the contention-free period, each node sends data using allocated channel and time slot. HyMAC guarantees low data latency and reliability, but sink node has insufficient problem of power and storage. In addition, control message and duplicated transmission can introduce extra energy consumption.

Purpose of MuChMAC(Multi-Channel MAC) [10] increases energy efficiency using convergecast and channel hopping. The convergecast is a mechanism which can support contention-free communication. Synchronization message which is broadcasted by sink node is not sent periodically. If sensor module is used for a long time, time drift is generated. Thus, when the time drift is intensified, the synchronization message will be sent. This method increases the energy efficiency because unnecessary synchronization message is not sent. But, frequent channel hopping and data duplication can also reduce energy efficiency and communication performance.

The single-radio multi-channel MAC protocols which can implemented on off-the-shelf sensor module are insufficient. Almost of these have unrealistic assumption about sink node or verify the performance using simulation result. Therefore, in this paper, we aim to propose a feasible single-radio multi-channel MAC protocols for WBAN to improve both the energy efficiency and the communication performance.

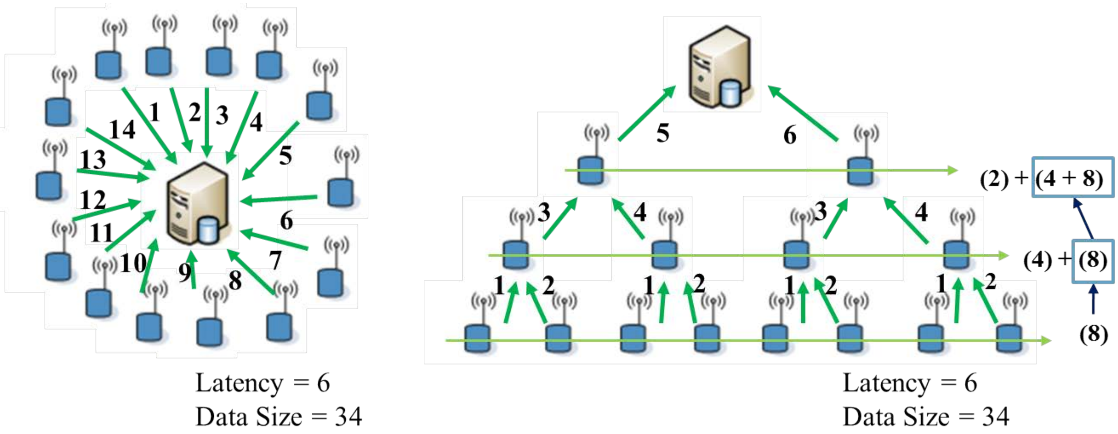
Chapter 3

Proposed Protocol

As referred to earlier, the MAC protocols based on multi-channel have serious problems, energy inefficiency, and unimplementable in off-the-shelf sensor module. To solve these problems, we propose a single-radio multi-channel MAC protocol based on a star plus mesh topology.

3.1 System Model

Baseline MAC protocol which uses single-radio single-channel is composed like Fig 3-1 (a). The arrow means direction of data transmission and the number on the arrow means order of the data transmission. As shown in Fig 3-1 (a), this protocol makes sequential data transmission to sink node. The major shortcoming of this protocol is high data latency because it needs more time slot for data transmission. To solve this problem, single-radio multi-channel MAC protocols based on tree topology are proposed. Fig 3-1 (b) is an example of single-radio multi-channel MAC protocol and this example uses 4 channels and 14 nodes. In (b) case, data can be transmitted faster than (a) case. However, data duplication may decrease the communication performance. More specifically, as shown in Fig 3-1 (b), data is sent step by step from source to



(a) Star topology protocol (b) Tree topology protocol

Fig 3-1: Previous MAC protocols

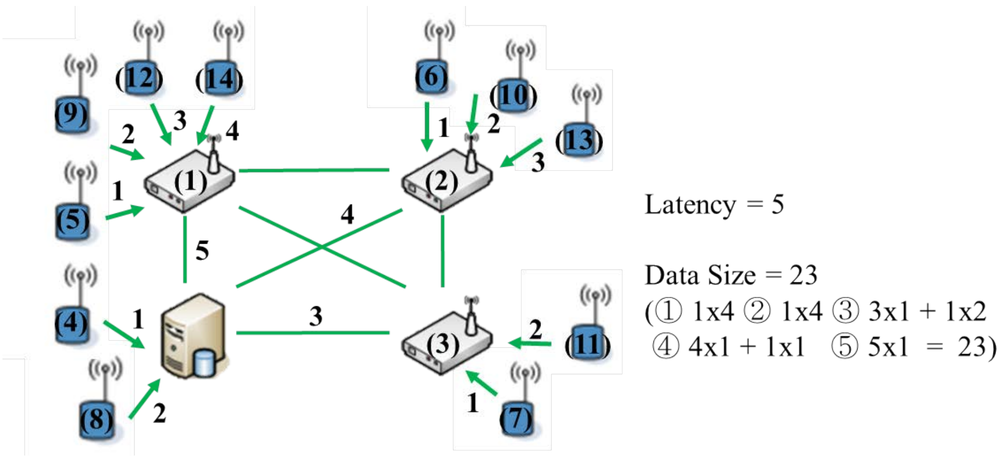


Fig 3-2: Proposed MAC protocol

sink node. In this reason, same data is transmitted several times so that it is able to seen as data size(totally sent data) is increased and this may result in energy inefficiency.

In this paper, we propose a single-radio multi-channel MAC protocol based on a star plus mesh topology to solve the limitation of existing works. Fig 3-2 shows an example of the proposed protocol. Likewise with Fig 3-1 (b), Fig 3-2 uses 4 channels and 14 nodes. The number on the circle means unique node number. To decrease data duplication and the number of required GTS slots, star topology is used. It reduces the data duplication, since it can guarantee the hop count to the nearest 2-hops and reduce the number of GTS slots because the coordinator aggregates data from other nodes and communicates in one time slot. As shown in Fig 3-2, this method can complement the energy inefficiency and data latency rather than Fig 3-1 (b).

The terms will be used in hereafter proposed formula and algorithm as follows:

- $\boldsymbol{N}$: The number of nodes except the sink node
- $\boldsymbol{C}$: The number of channels
- $\boldsymbol{n_i}$: node i $(1 \leq i \leq N)$
- $\boldsymbol{u_i}$: Unique number of node i
- $\boldsymbol{t_i}$: The type of node i
- $\boldsymbol{s_i}$: GTS starting slot of node i
- $\boldsymbol{l_i}$: The GTS length of node i
- $\boldsymbol{n_i^{des}}$: Destination node of node i
- $\boldsymbol{CS}$(Current Slot) : Currently used slot number

3.2 Network Topology and Proposed Protocol

Physical architecture is combination of star topology and mesh topology. In the star topology, each coordinator aggregates data of other nodes. In the mesh topology, sink node receives data from coordinators. The nodes in the network are divided into sink node, *DA*-node(Data Aggregation node) and *L*-node(Leaf node). All nodes comply with IEEE 802.15.4 [12] data format and superframe structure. The sink node collects all of data using unique channel. In addition, it has all of information of other nodes to take data or makes the time scheduling. *DA*-node plays a role as coordinator in star topology. It aggregates the data from *L*-nodes, other *DA*-nodes, and own by using receiving channel and sending channel. *L*-node sends the data to *DA*-node or the sink node using one channel. The number of star topology is $\boldsymbol{C}$. The sink node and *DA*-nodes function as coordinator of the star topology and *L*-nodes join to coordinator according to a proposed algorithm. The sink node and *DA*-nodes are element of the mesh topology. Composition process of the topology is performed as follows.

- Firstly, $(\boldsymbol{C}-1)$ indicates the numbers of node which are appointed to *DA*-node and each *DA*-node takes $\boldsymbol{u_i}$ from 1 to $(\boldsymbol{C}-1)$ sequentially.

- $\lfloor(\boldsymbol{N}+1)/\boldsymbol{C}\rfloor * \boldsymbol{C}$ indicates the numbers of node which join to the sink node and *DA*-nodes($\boldsymbol{n}_1, \boldsymbol{n}_2 \ldots \boldsymbol{n}_{(\boldsymbol{C}-1)}$) sequentially. ($\lfloor\boldsymbol{x}\rfloor$ makes largest integral value that is not greater than x.) Then, they take $\boldsymbol{u_i}$ from $\boldsymbol{C}$ to $(\mathbf{C}-1)+\lfloor(\boldsymbol{N}+1)/\boldsymbol{C}\rfloor * \boldsymbol{C}$. (For example, if $\boldsymbol{C}=4$ is assumed, $\boldsymbol{n}_4$ joins to the sink node, $\boldsymbol{n}_5$ joins to the *DA*-node($\boldsymbol{n}_1$), $\boldsymbol{n}_6$ joins to the *DA*-node($\boldsymbol{n}_2$) and $\boldsymbol{n}_7$ joins to the *DA*-node($\boldsymbol{n}_3$) and repeat this process.)

- The remained nodes sequentially join to the *DA*-nodes ($\boldsymbol{n}_1, \boldsymbol{n}_2 \ldots \boldsymbol{n}_{(\boldsymbol{C}-1)}$) excepted $\boldsymbol{n}_{(\boldsymbol{C}-1)}$. Then, they take $\boldsymbol{u_i}$ from $\boldsymbol{C}+\lfloor(\boldsymbol{N}+1)/\boldsymbol{C}\rfloor * \boldsymbol{C}$ *to* $\boldsymbol{N}$. When finish this work, sink node

Algorithm for topology construction

$\boldsymbol{i}$=0
WHILE i<($\boldsymbol{N}$+1) **DO**
    $\boldsymbol{u_i} = \boldsymbol{i}$
    IF ($\boldsymbol{i}$==0) **THEN**
        insert the information of sink node into the $\boldsymbol{n_i}$
        $\boldsymbol{t_i}$ = SINK_NODE
    ELSE IF ($\boldsymbol{i}$<=($\boldsymbol{C}$+1)) **THEN**
        insert the information of *DA*-node into the $\boldsymbol{n_i}$
        $\boldsymbol{t_i}$ = DA_NODE
    ELSE
        insert the information of *L*-node into the $\boldsymbol{n_i}$
        $\boldsymbol{t_i}$ = L_NODE
        $\boldsymbol{n_i^{des}} = \boldsymbol{n}_{((\boldsymbol{i}\%\boldsymbol{C})+\boldsymbol{1})}$
    ENDIF
    Add 1 to $\boldsymbol{i}$
ENDWHILE

Fig 3-3. Topology construction algorithm

and *DA*-nodes compose the mesh topology.

The pseudo-code description of the algorithm is given in Fig 3-3. When the composition process is finished, data transmission process is performed as follows.

- Firstly, each coordinator of star topologies receives data from *L*-nodes. When several *L*-

Header	Superframe Specification	Channel	...	Address	Number	Address	Number	...

Fig 3-4: Beacon frame structure

Algorithm for GTS allocation (Star topology)

$\boldsymbol{i}=\boldsymbol{C}$
WHILE $\boldsymbol{i}$<($\boldsymbol{N}$+1) **DO**
    IF ($\boldsymbol{i}$<(($\boldsymbol{N}$+1)/$\boldsymbol{C}$)*$\boldsymbol{C}$) **THEN**
        $\boldsymbol{s_i}$= ($\boldsymbol{i}$/$\boldsymbol{C}$)
    ELSE
        IF ($\boldsymbol{n_i^{des}.t_i}$ == *DA*-NODE) **THEN**
            $\boldsymbol{s_i}$ = ($\boldsymbol{i}$/$\boldsymbol{C}$)
        ENDIF
    ENDIF
    Add 1 to $\boldsymbol{i}$
ENDWHILE

Fig 3-5: GTS allocation algorithm (Star topology)

nodes use the same GTS slot, different channels are allocated to each *L*-node. As shown in the Fig 3-2, $\boldsymbol{n}_4, \boldsymbol{n}_5, \boldsymbol{n}_6, \boldsymbol{n}_7$ firstly send the data. They use the same GTS slot and different channels. $\boldsymbol{n}_8, \boldsymbol{n}_9, \boldsymbol{n}_{10}, \boldsymbol{n}_{11}$ secondly send the data and use the same process.

Algorithm for GTS allocation (Mesh topology)

$\boldsymbol{k}$, $\boldsymbol{i}$=(($\boldsymbol{N}$+1)/$\boldsymbol{C}$)
WHILE ∞ **DO**
  $\boldsymbol{k}$=0, $\boldsymbol{j}$=0
  WHILE $\boldsymbol{j}$<C **DO**
    IF ($\boldsymbol{s_i}$==0 && $\boldsymbol{s_i}$<=$\boldsymbol{i}$) **THEN**
      insert the information of $\boldsymbol{n_j}$ into temp[$\boldsymbol{k}$]
      Add 1 to $\boldsymbol{k}$
    ENDIF
    Add 1 to $\boldsymbol{j}$
  ENDWHILE
  IF ($\boldsymbol{k}$==0) **THEN** : break
  $\boldsymbol{max}$ = $\boldsymbol{n_i}$ which have the most data size
  temp[$\boldsymbol{max}$].$\boldsymbol{s_i}$= $\boldsymbol{i}$
  $\boldsymbol{j}$=($\boldsymbol{k}$-1)
  WHILE $\boldsymbol{j}$<=0 **DO**
    IF (data size of temp[$\boldsymbol{j}$-1] is larger than temp[$\boldsymbol{j}$]) **THEN**
      temp[$\boldsymbol{j}$].$\boldsymbol{s_i}$= $\boldsymbol{i}$
      temp[$\boldsymbol{j}$].$\boldsymbol{n_i^{des}}$ = temp[j-1].$\boldsymbol{n_i}$
    ELSE
      temp[$\boldsymbol{j}$-1].$\boldsymbol{s_i}$= $\boldsymbol{i}$
      temp[$\boldsymbol{j}$-1].$\boldsymbol{n_i^{des}}$ = *temp[$\boldsymbol{j}$]*.$\boldsymbol{n_i}$
    ENDIF
    Subtract 2 to $\boldsymbol{j}$
  ENDWHILE
ENDWHILE

Fig 3-6: GTS allocation algorithm (Mesh topology)

Algorithm for Communication Flow (Sink node)

```
CS=0 (In timer interrupt, CS is changed)
WHILE TRUE DO
    IF ( CS==0 ) THEN
        send the beacon signal
    ELSE IF ( CS<aNumSuperframeSlots ) THEN
        receive the data from other nodes
    ELSE
        sleep()
    ENDIF
ENDWHILE
```

Fig 3-7: Communication Flow algorithm (Sink node)

- *DA*-nodes that completely collect data from *L*-node are grouped. One of *DA*-nodes which have maximum data size in this group sends the data to sink node in next GTS slot and in the same GTS slot, one of *DA*-nodes that have the minimum data size sends the data to *DA*-node that has the maximum data size among remainder. Repeatedly do this process when all of *DA*-nodes take the operation which transmission or reception.

According to this method, we can reduce the number of GTS slots. Each *DA*-node aggregates the data when the number of channels($\boldsymbol{CS}$) is not same with own GTS starting slot($\boldsymbol{s_i}$). When the $\boldsymbol{CS}$ is same with the own $\boldsymbol{s_i}$, *DA*-node sends the aggregated data using one GTS slot. For example, in Fig 3-2, $\boldsymbol{n_1}, \boldsymbol{n_5}, \boldsymbol{n_9}, \boldsymbol{n_{12}}, \boldsymbol{n_{14}}$ originally use five numbers of GTS slots, but this method uses only one GTS slot.

Algorithm for Communication Flow (*DA*-node)

```
CS=0 (In timer interrupt, CS is changed)
change the channel to sink node's channel
WHILE TRUE DO
    IF ( CS==0 ) THEN
        take and analyze the beacon signal
    ELSE IF ( CS>=s_i && CS<s_i + l_i ) THEN
        change the channel to sending channel
        send the data
    ELSE IF ( CS<s_i && CS>=s_i + l_i
                && CS< aNumSuperframeSlots ) THEN
        change the channel to receiving channel
        receive the data from other nodes
    ELSE
        change the channel to sink node's channel
        sleep()
    ENDIF
ENDWHILE
```

Fig 3-8: Communication Flow algorithm (*DA*-node)

When the each node knows the own unique number($\boldsymbol{u_i}$), the nodes automatically conduct the communication process according to the algorithm. Therefore, the sink node sends the beacon signal to every node using the first slot in superframe structure. The beacon signal includes the information about $\boldsymbol{u_i}$ that each node will use. Fig 3-4 represents the beacon frame structure. In

Algorithm for Communication Flow (L-node)

```
CS=0 (In timer interrupt, CS is changed)
change the channel to sink node's channel
WHILE TRUE DO
    IF ( CS==0 ) THEN
        take and analyze the beacon signal
    ELSE IF ( CS>=s_i && CS<s_i + l_i ) THEN
        change the channel to sending channel
        send the data
    ELSE
        change the channel to sink node's channel
        sleep()
    ENDIF
ENDWHILE
```

Fig 3-9: Communication Flow algorithm (L-node)

header, the message type, sequence number and the address of the source are included. And in the Superframe Specification field, BO(Beacon Order), and SO(Superframe Order) are included. The remainder represents the available channels and $\boldsymbol{u_i}$ that will be allocated to each node. When the nodes take the beacon signal, they check the Address field. If the Address field same with its own address, the nodes set the Number field which is the next field of the checked Address field to the own unique number.

3.3 GTS Allocation

Every node communicates with other node based on own GTS starting slot($\boldsymbol{s_i}$). The $\boldsymbol{s_i}$ is changed according to own unique number($\boldsymbol{u_i}$). Fig 3-5 and 3-6 shows the algorithm which is utilized to allocate the $\boldsymbol{s_i}$. Every node is taken the own $\boldsymbol{u_i}$ by beacon signal. If many nodes take the same slot, each node uses the different channels.

When the currently used slot number($\boldsymbol{CS}$) is contained between $\boldsymbol{s_i}$ to ($\boldsymbol{s_i}$+$\boldsymbol{l_i}$), $\boldsymbol{n_i}$, changes the channel to sending channel. It is same with destination node's channel which is currently occupied. In contrast, $\boldsymbol{CS}$ is not contained between $\boldsymbol{s_i}$ to *(*$\boldsymbol{s_i}$+$\boldsymbol{l_i}$*)*, $\boldsymbol{n_i}$, changes the channel to receiving channel. This method can reduce the collision and guarantee the reliable communication. In addition, it is efficient to complement the energy inefficiency because unnecessary CCA(Clear Channel Assessment) is reduced.

The flow algorithms of each node in this communication are represented as shown in Fig 3-7, 3-8 and 3-9. Every node uses the time synchronization based on IEEE 802.15.4 superframe structure. In Fig 3-7, 3-8 and 3-9, aNumSuperframeSlots means the maximum number of time slot, and $\boldsymbol{CS}$ is the current slot number that program use. When the $\boldsymbol{CS}$ is equal to 0, beacon signal is sent by sink node. Then *DA*-nodes and *L*-nodes take the beacon signal and notice about own information which are $\boldsymbol{u_i}$, type of node($\boldsymbol{t_i}$), $\boldsymbol{s_i}$, destination of node ($\boldsymbol{n_i^{des}}$), and GTS length of node($\boldsymbol{l_i}$). Since the $\boldsymbol{CS}$ is larger than 0, every node except the sink node sends the data to own $\boldsymbol{n_i^{des}}$ when the $\boldsymbol{CS}$ is between own $\boldsymbol{s_i}$ and ($\boldsymbol{s_i}$+$\boldsymbol{l_i}$). In other time slot, *DA*-nodes receive the data from other nodes, and *L*-nodes enter to sleep state. When the $\boldsymbol{CS}$ is larger than aNumSuperframeSlots, every node waits the next beacon signal.

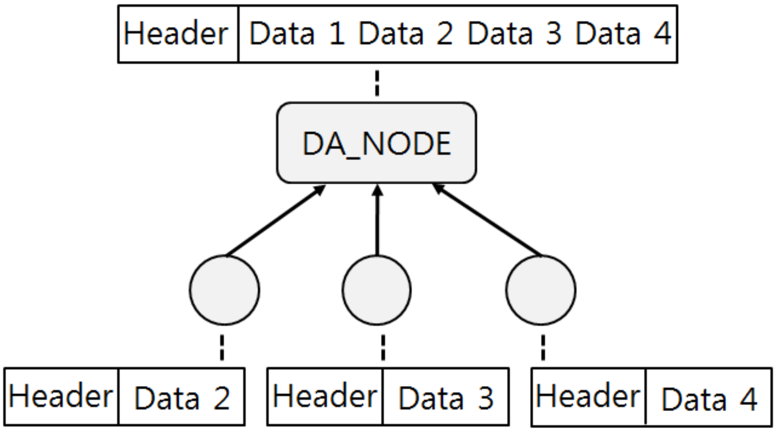


Fig 3-10: Data Aggregation

3.4 Data Aggregation

This protocol basically uses data aggregation process when *DA*-nodes take data from *L*-nodes or other *DA*-nodes. Fig 3-10 represents the data aggregation process. *L*-node send the Data 2,3,4 and *DA*-node will send the Data 1. When the data aggregation process is done, *DA*-node has the Data 1,2,3,4. This aggregated data will be transmitted using one GTS slot. Thus, this process can not only reduce the number of GTS slot but also minimize data latency.

Chapter 4

Performance Evaluation

Purposes of the proposed protocol reduce data latency and duplicate data size. As mentioned before, our MAC protocol is feasible for implementation on off-the-shelf sensor node because it is designed based on single-radio.

Firstly, we present result of analysis compared with HyMAC, MuChMAC, and baseline MAC protocol. The number of channels $(\boldsymbol{C})$ is fixed to 4 and the number of nodes$(\boldsymbol{N})$ is not fixed. $\boldsymbol{N}$ is changed from 1 to 64. Secondly, we present result of measurement compared with the baseline MAC protocol. Like as the analysis, $\boldsymbol{C}$ is fixed to 4 and $\boldsymbol{N}$ is not fixed. In our measurement, we use ZigbeX-I and ZigbeX-II modules which support the multi-channel communication by using CC2420 RF transceiver as shown in Fig 4-1.

Every node uses the superframe structure which is standardized by IEEE 802.15.4. Fig 4-2 shows the superframe structure. Supeframe is divided into active portion and inactive portion. Active portion is subdivided into CAP and CFP. The CAP is contention period and the CFP is contention-free period. In the measurement, we only use the CFP period. It includes the GTS slot that node can be communicated without collision, and maximum number of GTS slot at one superframe is 7.

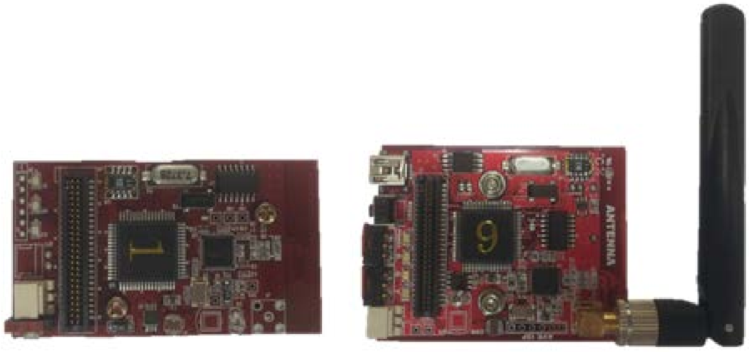


Fig 4-1: ZigbeX-I and ZigbeX-II

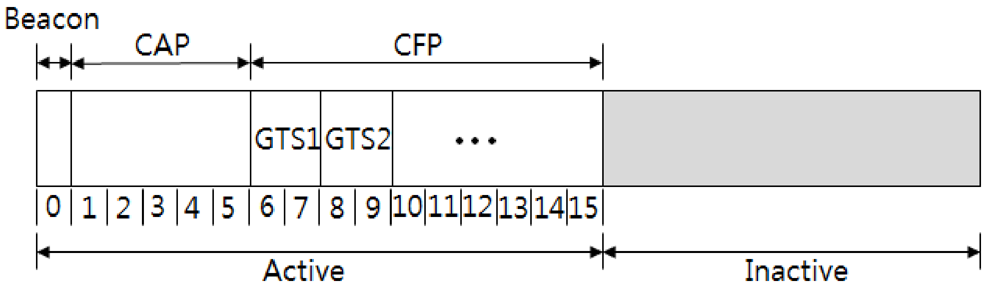


Fig 4-2: Superframe structure

The performance factors are data latency and data size. We observe change of these factors when the $\boldsymbol{N}$ is gradually increased.

4.1 Data Latency

If a protocol needs the excessive GTS slots, it can increase the delay. Thus, data latency represents how many GTS slot is needed.

4.1.1 Result of Analysis

Baseline MAC protocol makes high data latency because sequential sending of data need a lot of GTS slots. If the number of GTS slot is more than 7, the node will use one more superframe because one superframe can maximally use 7 number of GTS slots. But, the proposed MAC protocol, HyMAC, and MuChMAC reduce the number of GTS slot based on inventive topology and multi-channel. In this section, we assume that topology of HyMAC is binary tree. The formulas of the data latency are presented in Table 4.1. $\boldsymbol{G_N}$ means that how many GTS slots are needed according to the number of nodes($\boldsymbol{N}$). Fig 4-3 presents the graph of the data latency according to the equations in Table 4.1. As shown in the Fig 4-3, data latency of proposed MAC protocol is smaller than the others.

Table 4.1: Formulas of data latency

Protocol	**Data latency (# of GTS slots)**
Baseline MAC	$\boldsymbol{G_N} = \boldsymbol{N}, \qquad (1 \le \boldsymbol{N} \le 64)$
MuChMAC	$\boldsymbol{G_N} = \left\lfloor \frac{\boldsymbol{N}}{2} \right\rfloor + 1, \qquad (1 \le \boldsymbol{N} \le 64)$
HyMAC	$\boldsymbol{G_N} = \left\lfloor \frac{\boldsymbol{N}}{2} \right\rfloor + 1, \qquad (1 \le \boldsymbol{N} \le 5)$ $\boldsymbol{G_N} = \left\lfloor \frac{\boldsymbol{N}-2}{4} \right\rfloor + 3, \qquad (6 \le \boldsymbol{N} \le 64)$
Proposed MAC (ISRMC-MAC)	$\boldsymbol{G_1} = 1 \qquad (\mathrm{N} = 1)$ $\boldsymbol{G_N} = \left\lfloor \frac{\boldsymbol{N}}{4} \right\rfloor + 2, \qquad (2 \le \boldsymbol{N} \le 64)$

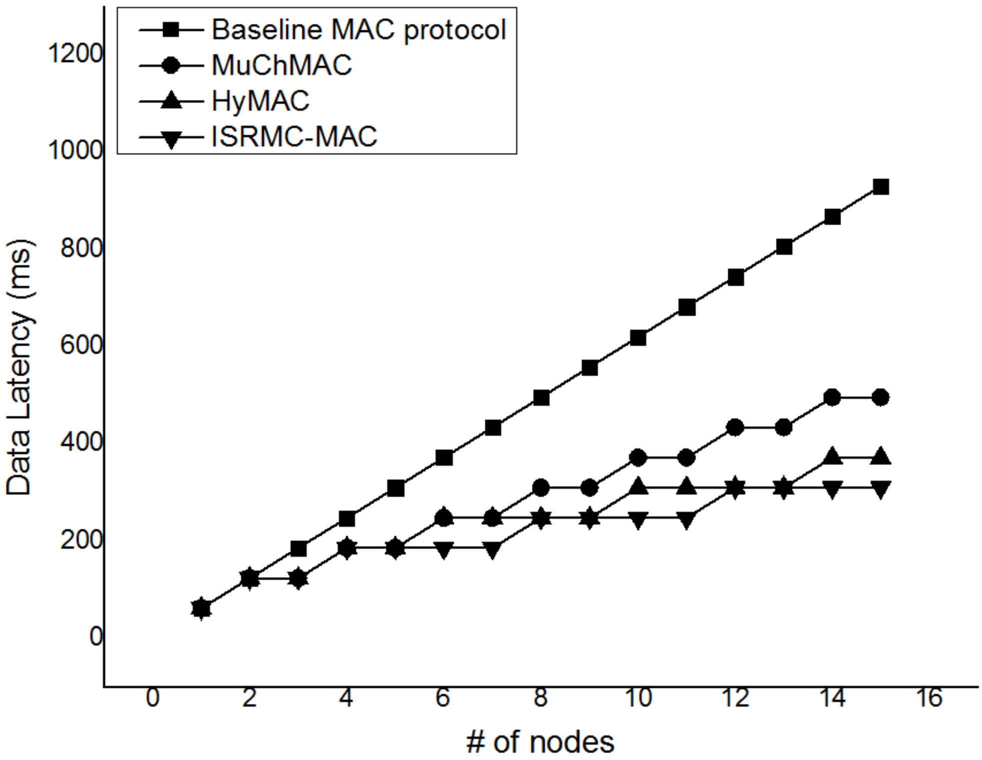


Fig 4-3: Analysis result of data latency

4.1.2 Result of Measurement

Fig 4-4 presents the result of measurement. The BO(Beacon Order) and SO(Superframe Order) of the superframe are set to 10. In this condition, inactive period is not used and the time of the one slot is 62ms. The gap between baseline MAC protocol and proposed MAC protocol is similar with the result of analysis. It can verify that the proposed MAC protocol reduces the data latency in real environment.

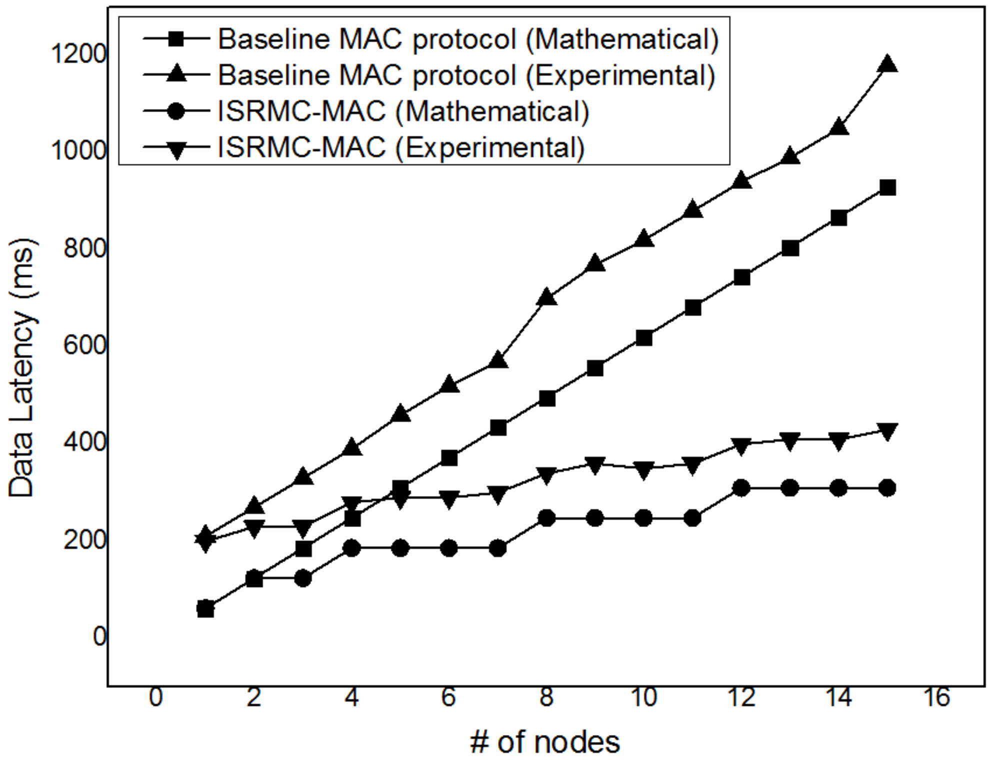


Fig 4-4: Measurement result of data latency

4.2 Data Size

Data size represents that how many duplication is occurred. Excessive duplications may result in the energy inefficiency.

4.2.1 Result of Analysis

Baseline MAC protocol does not have this problem because it sends the data directly to sink node. However, HyMAC and MuChMAC which employ tree-based topology and transmit

Table 4.2: Equation of data size

Protocol	Data latency (# of data duplication)
Baseline MAC	$\boldsymbol{D_N} = \boldsymbol{N}, \qquad (1 \le \boldsymbol{N} \le 64)$
MuChMAC	$\boldsymbol{D_N} = 1$ $\boldsymbol{D_N} = \boldsymbol{D_{N-1}} + \left\lfloor \frac{\boldsymbol{N}+1}{2} \right\rfloor, \qquad (2 \le \boldsymbol{N} \le 64)$
HyMAC	$\boldsymbol{D_N} = 1$ $\boldsymbol{D_N} = \boldsymbol{D_{N-1}} + \lfloor \log_2(\boldsymbol{N}+1) \rfloor, \qquad (2 \le \boldsymbol{N} \le 64)$
Proposed MAC (ISRMC-MAC)	$\boldsymbol{D_N} = \boldsymbol{N}, \qquad (1 \le \boldsymbol{N} \le 2)$ $\boldsymbol{D_N} = \boldsymbol{D_{N-1}} + \left\lfloor \frac{\boldsymbol{N}+5}{4} \right\rfloor, \qquad (\boldsymbol{N} = 3,7,11 \dots)$ $\boldsymbol{D_N} = \boldsymbol{D_{N-1}} - \left\lfloor \frac{\boldsymbol{N}-8}{4} \right\rfloor, \qquad (\boldsymbol{N} = 4,8,12 \dots)$ $\boldsymbol{D_N} = \boldsymbol{D_{N-1}} + 2, \qquad (Other\text{wise})$

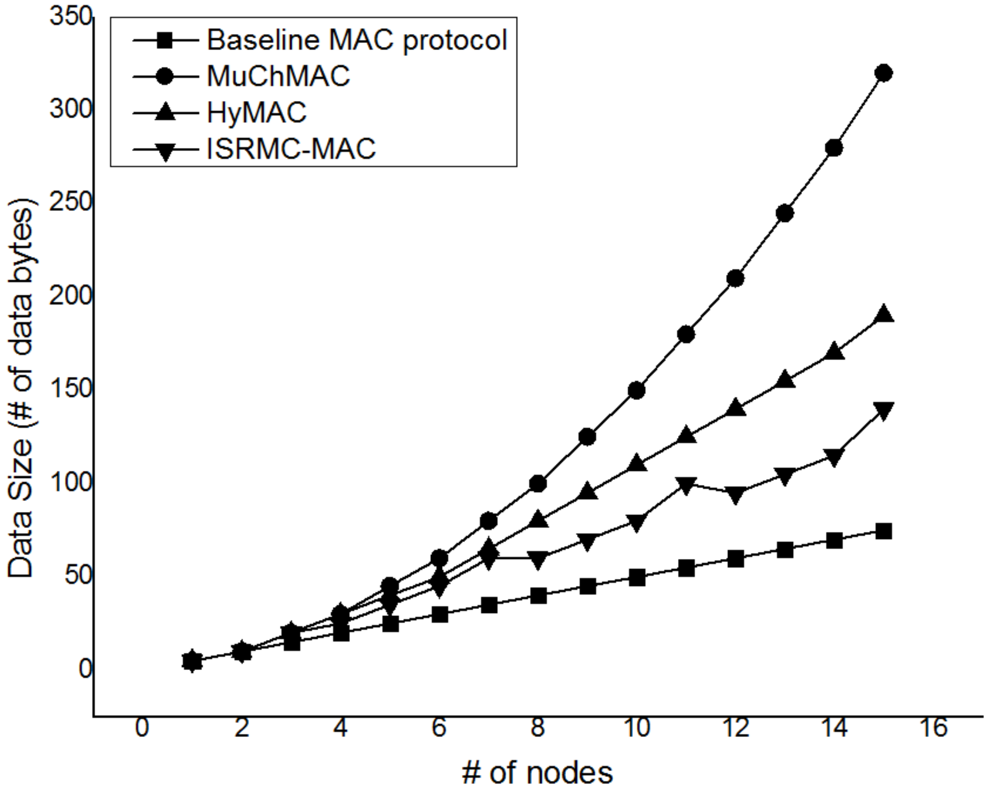


Fig 4-5: Analysis result of data size

packets to sink node through multi-hop still have this problem. The reason is that the parent nodes repeatedly send the data which came from child nodes. Thus, proposed MAC protocol reduces this based on star plus mesh topology.

This topology guarantees the minimum hop sending process to all nodes. Table 4.2 represents the formulas of the data size. $\boldsymbol{D_N}$ means that how many duplications are generated according to the number of nodes($\boldsymbol{N}$). Fig 4-5 presents the transition of the data size according to the equations in Table 4.2. As shown in the Fig 4-5, proposed MAC protocol strictly reduces

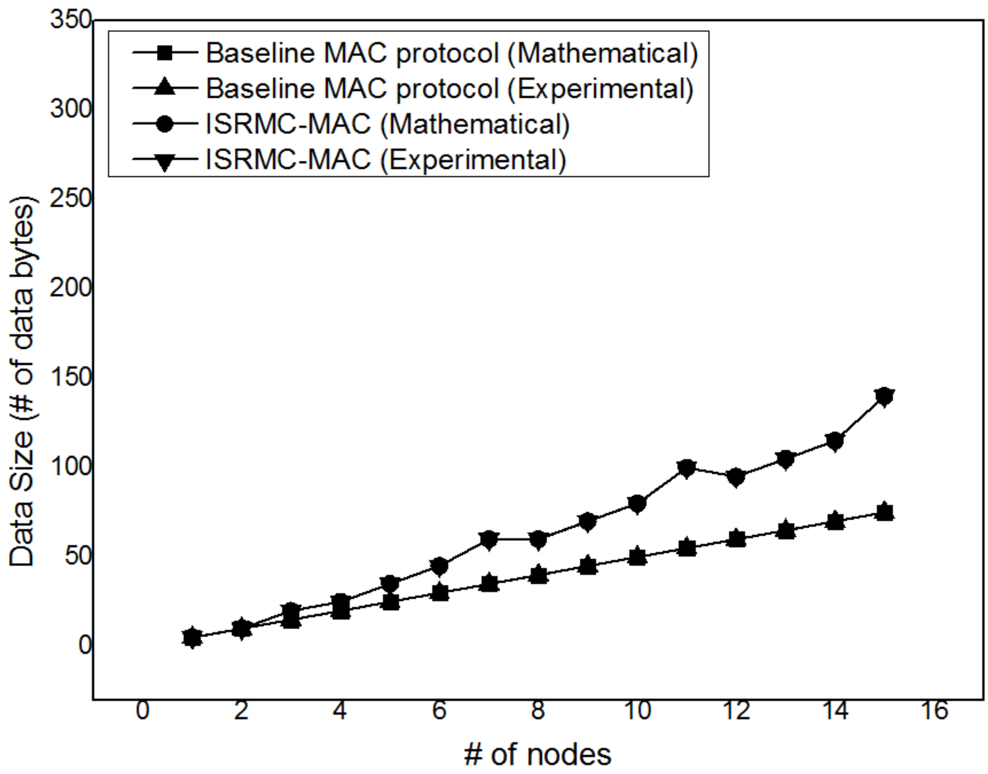


Fig 4-6: Measurement result of data size

the data size rather than HyMAC and MuChMAC. Existing single-radio multi-channel MAC protocol has the energy inefficiency on account of the data duplication. But, proposed MAC protocol complements this problem based on inventive topology and algorithm.

4.2.2 Result of Measurement

Fig 4-6 presents the result of measurement. Each node sends 10 bytes. The gap between baseline MAC protocol and the proposed MAC protocol is similar with the result of analysis. Thus, it can verify that proposed MAC protocol complements the energy inefficiency rather than baseline MAC protocol.

Chapter 5

Conclusion

WBAN requires the low data latency, since the medical data should be sent timely and correctly. Furthermore, it should be guaranteed the energy efficiency because the tiny sensor has the limited energy capacity. Thus, a lot of MAC protocols have been proposed, but they have many limitations. For this reason, we propose the single-radio multi-channel MAC protocol which can improve the network performance and energy efficiency. More specially, we design a novel GTS allocation algorithm and a topology composition algorithm for star plus mesh topology. And then we verify this protocol uses the real sensor modules, ZigbeX-I and ZigbeX-II. As shown in Section 4, data latency and data size are significantly reduced.

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