Thesis for the Degree of Doctor of Philosophy

Energy-efficient, Reliable, and Flexible Data Transmission in Wireless Personal Area Networks

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Abstract

Wireless personal area network (WPAN) is a standard for wireless communication with short range such as a space around a person. Because of the demand for low power, low cost wireless communication, a low-rate WPAN (LR-WPAN) comes out. Wireless sensor network (WSN) recognizes a wireless technology to support the LR-WPAN services. The WSN consists of a large number of tiny sensor nodes. It constructs ad-hoc network and monitors physical phenomena. Thus it is considered a base technology to implement a ubiquitous computing environment. Since the tiny sensor nodes have limited resources, routing algorithms for WSN should be energy-efficient. Cluster-based hierarchical routing algorithms are known to be more efficient than flat routing algorithms because only cluster-heads communicate with a sink node. Existing hierarchical routing algorithms, however, assume unrealistically large radio transmission ranges of sensor nodes so they cannot be employed in a real environment. Therefore, considering practical transmission range of the sensor nodes, this thesis proposes a clustering and routing method for hierarchical sensor networks: The proposed clustering algorithm provides the optimal ratio of cluster-heads and a clustering scheme which expands the range of clusters until d-hop calculated by the ratio of cluster-head. The proposed routing method provides an intra-cluster routing to transmit data from source nodes to their cluster-head and an inter-cluster routing to deliver data from cluster-heads to a sink node. The efficiency of the proposed clustering and routing method is validated through extensive simulations.

In WSN, due to high packet loss rate during multi-hop transmissions, reliable end-to-end data transmission is desirable. Because WSN applications require various levels of communication reliability (CR), the end-to-end data transmission should satisfy the desired CR of the applications. This thesis proposes a flexible loss recovery mechanism for WSN applications with various CRs to reliably transmit data packets. The mechanism caches data packets at intermediate nodes over routing paths computed by CR to retransmit lost packets during multi-hop transmissions. Because it presents a tradeoff between end-to-end delays and memory requirements dependent on CR, it can be used flexibly in various WSN applications. In addition, for the loss recovery, sensor nodes need to keep data packets in their buffers until transmissions successfully complete. However, since the sensor nodes have limited memory, the packets cannot be maintained for a long period of time. Thus, this thesis proposes an efficient buffer management that caches data packets for appropriate amount of time to minimize the resource requirements.

In WPAN, recent advances have evolved to provide various services, with healthcare being the most frequently provided service. However, WSN such as LR-WPAN reaches the limit to provide various smart services because it has only been designed for medical healthcare information. Smart services of WPAN provide both medical and consumer electronics (CE) applications. For the smart services, a wireless body area network (WBAN) has recently issued a next generation wireless technology of WPAN. WBAN functions in the vicinity of, on, or inside a human body and supports heterogeneous devices (i.e., medical and non-medical (CE) devices). Since it utilizes both MICS frequency band for implant medical applications and ISM frequency band for medical and CE applications, MAC protocols in WBAN should be designed considering flexibility between medical and CE applications. This thesis identifies the requirements of WBAN MAC and proposes a novel WBAN MAC which satisfies the requirements: The proposed WBAN MAC provides a dynamic CFP allocation and an opportunity period for transmission flexibility. Extensive simulation results show the novel MAC achieves improved throughput and latency in WBAN compared with IEEE 802.15.4 MAC of LR-WPAN.

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Chapter 1

Introduction

1.1 Motivation

Wireless personal area network (WPAN) is a communication technology within short distance. It focuses on low-power, low-cost, and low-complexity of wireless communication. Thus, WPAN is recognized as a base technology for ubiquitous services. The ubiquitous services provide controlling or monitoring applications. Wireless sensor network (WSN) and wireless body area network (WBAN) support WPAN to implement the applications. They have battery-based power sources and operate over a harsh radio channel. Therefore, data transmission in WPAN should consider following three terms:

- *Energy-efficient*: Devices for WPAN have limited power sources and a particular application of WPAN may require two years battery life. For long lifetime, the energy-efficient system should be considered for data transmission.
- *Reliable*: Multi-hop transmission consumes less energy but causes high packet losses over wireless link. Since accurate and timely information may be crucial for WPAN services, reliable transmission is essential.
- *Flexible*: Devices for WPAN have various characteristics. They require various levels of reliability or generate various traffic with different characteristics (i.e., medical or non-medical). Thus, data transmission methods in WPAN provide the flexibility.

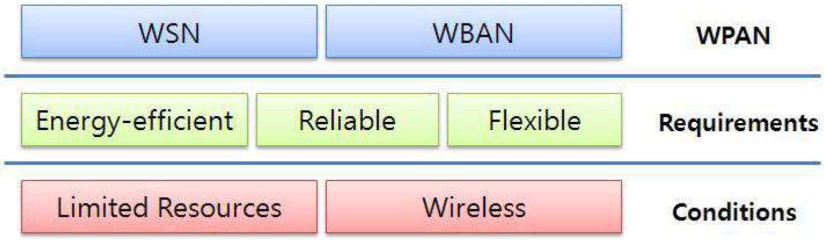


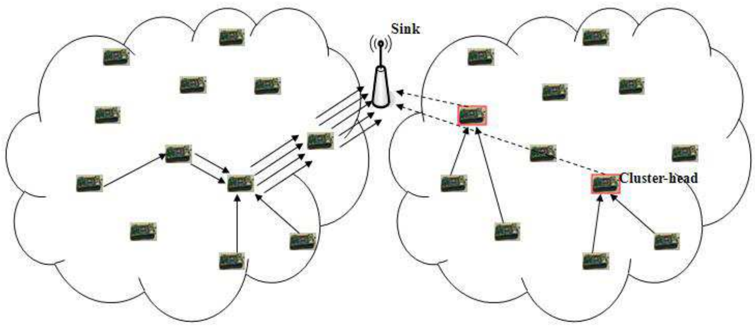
Figure 1.1: Data transmission in WPAN.

As shown in Figure 1.1, in the wireless condition, WPAN with restrict resources should satisfy the requirements (i.e., energy-efficiency, reliability, and flexibility) for various services. Thus, this thesis handles following subjects: a cluster-based transmission technology, a reliable transmission technology, and a flexible WBAN MAC. A cluster-based transmission technology is energy-efficient in WSN. By a reliable transmission technology, the given communication reliability of application traffic can be guaranteed. In addition, for WBAN with various traffic characteristics, a flexible WBAN MAC scheme should be provided.

1.2 Contribution

The first part of the thesis deals with practical data transmission of the cluster-based sensor networks. Typically, the energy consumption for data transmission takes the highest portion of total energy consumption in WSN [1]. Nodes of WSN have limited power sources. Thus, data transmission method of WSN as the LR-WPAN should be designed by considering such low-power requirement.

Routing protocols for data transmission in WSN are classified into two types: flat routing protocols and hierarchical routing protocols. Hierarchical routing protocols have fewer data transmissions than flat routing protocols because the number of total data transmissions is smaller in the network. Each cluster-head compresses and aggregates



(a)Flat routing protocol (b)Hierarchical routing protocol

Figure 1.2: Wireless sensor network routing protocols.

data from slave nodes within its cluster. Cluster-based hierarchical routing protocols therefore show better performance than flat routing protocols [1]. Figure 1.2 shows data transmissions of flat routing and hierarchical routing protocols.

In hierarchical routing protocols which have been studied in the context of wireless networks, clustering methods are mainly considered [2, 3, 4, 5, 6]. Conventional hierarchical routing protocols in WSNs do not consider inter-cluster communication because they assume that cluster-heads can communicate with the sink node directly. IEEE 802.15.4 (LR-WPAN), however, which is one of the transmission standards for WSNs, is focused on 'Personal Operating Space' (POS[1]) that typically extends up to 10m in all directions [7, 8].

Neither cluster-heads nor sensor nodes can transmit data directly over POS. Although there are several studies on heterogeneous hierarchical sensor networks, composed of low power sensor nodes and more powerful cluster-heads [9, 10], it is unrealistic to suggest that positions of cluster-heads should be determined a priori. Thus, conventional hierarchical routing protocols cannot be employed in a practical environment. Figure 1.3 depicts the aforementioned problems which assume an unrealistic environment. First,

[1]POS means a space around person or object.

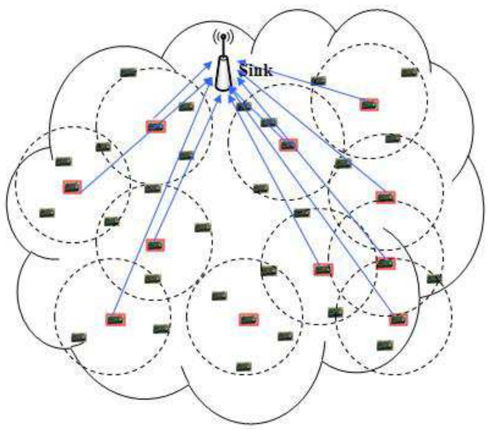


Figure 1.3: Problems of hierarchical routing protocols.

since transmission radio distance is less than 10m in POS and thus the diameter of each cluster is less than 10m in conventional clustering algorithms, many clusters must be organized. Numerous clusters lead to large communication overhead so that the network lifetime may be reduced. Next, every cluster-head cannot transmit data to the sink node directly because its transmission radius is the same as that of other sensor nodes within the POS.

For exploiting WSN in a practical environment, POS should be considered. One of the major focuses of the thesis is to achieve a practical data transmission in cluster-based WSN. To accomplish this, a proper ratio of clusters to minimize energy consumption is determined. In the POS environment, more clusters can generate than the ratio. So, the proposed clustering scheme in the thesis expands the range of clusters to maintain the ratio of clusters. In addition, to communicate with a sink node, this thesis suggests multi-hop transmission within the POS range.

The second part of the thesis concentrates on reliable data transmission. Wireless channel causes high packet loss during multi-hop transmission in WSN. Reliable data transmissions are required for various WSN applications. Thus, communication systems in end-to-end data transmission of WSN employ a recovery mechanism for lost data. There are two types of loss recovery mechanisms used in reliable end-to-end transmissions for event-driven applications: *end-to-end* loss recovery and *hop-by-hop* loss recovery [11, 12]. End-to-end loss recovery schemes request retransmissions of lost packets from the source node, while hop-by-hop loss recovery schemes request retransmissions of lost packets from an intermediate or a relay node that caches a copy of the data. Data in WSNs requires different levels of *communication reliability* (CR) per application service. In order to satisfy the desired end-to-end CR of an application, applying one recovery technique or the other to all data traffic is not suitable [13]. For this reason, this thesis proposes a flexible loss recovery technique that determines based on CR the most appropriate relay nodes in a routing path to cache the data.

Although the loss recovery mechanism is used, multiple data flows cause excessive use of buffers and increase memory requirements of sensor nodes. Since sensor nodes have limited resources, an efficient buffer management together with the loss recovery mechanism is required to provide reliable data transmissions. Thus, this thesis also proposes an efficient buffer management technique.

Recent attentions to healthcare and lifecare have provided driving forces behind WPAN studies. WBAN becomes the next generation of wireless technology for the WPAN. The WBAN allows applications with different characteristics. We assume that medical applications have periodic characteristics with a low data rate and CE applications are event-driven in nature with a high data rate such as entertainment video clips. Therefore, WBAN should support both medical and CE devices simultaneously. However, existing MAC protocols (i.e., TDMA or IEEE 802.15.4 MAC) [14], which are being used in WBAN, do not satisfy the requirements in the specification of the IEEE 802.15.6. So, the third part of the thesis focuses on WBAN MAC protocol and a novel WBAN MAC protocol to satisfies the requirements is proposed.

1.3 Organization of the thesis

The reset of the thesis is organized as follows: Chapter 2 briefly introduces background for WPAN, WSN, and WBAN.

Chapter 3 presents the proposed clustering algorithm and data transmission for the hierarchical routing in WSN. This chapter analyzes a practical environment for WSN and describes efficient data transmission method for the environment.

Chapter 4 depicts the proposed loss recovery mechanism for reliable data transmission and an efficient buffer management technique for the loss recovery mechanism. This chapter models the proposed loss recovery mechanism via numerical analysis and compares it with computer simulation results. In addition, a buffer management technique based on the analysis model is explained.

Chapter 5 describes a novel WBAN MAC protocol. This chapter identifies the requirements of WBAN MAC protocols and suggests a WBAN MAC protocol which satisfies the requirements.

Finally chapter 6 concludes the thesis with future directions and opened research issues from the proposed comprehensive works.

Chapter 2

Background

2.1 Wireless Personal Area Network

Wireless personal area network (WPAN) [15] is used to deliver data within relatively short distances. Unlike wireless local area network (WLAN) [16], wireless connections of WPAN involve no infrastructure. For the WPAN standardization, the IEEE 802.15 working group (WG) was organized. The IEEE 802.15 WG intends to support ubiquitous wireless communication in short-range without restriction. The WPAN has evolved three groups: First group is Bluetooth [17] (IEEE 802.15.1) to replace wire cables. Second group is high-rate WPAN [18] (HR-WPAN: IEEE 802.15.3) for wireless connections of digital appliances for multimedia. Final group is low-rate WPAN [19] (LR-WPAN: IEEE 802.15.4) to support low-complexity, low-cost, and low-power applications. Each group of WPAN is differentiated by data rate and quality of service (QoS) of applications. Figure 2.1 shows the operating space of the WPAN groups.

Most of ubiquitous computing services (e.g., industrial, agricultural, vehicular, residential, healthcare applications) generate sensing information [20, 21, 22]. Systems exploit the sensing information for controlling and monitoring. Thus, LR-WPAN has been the most important position among WPAN technologies. LR-WPAN supports star or mesh topology and provides maximum 250 kbps as data rate. In addition, LR-WPAN has a personal operating space (POS) as an operating range. POS is a space around a person or object that typically extends up to 10m in all directions [7, 8, 23].

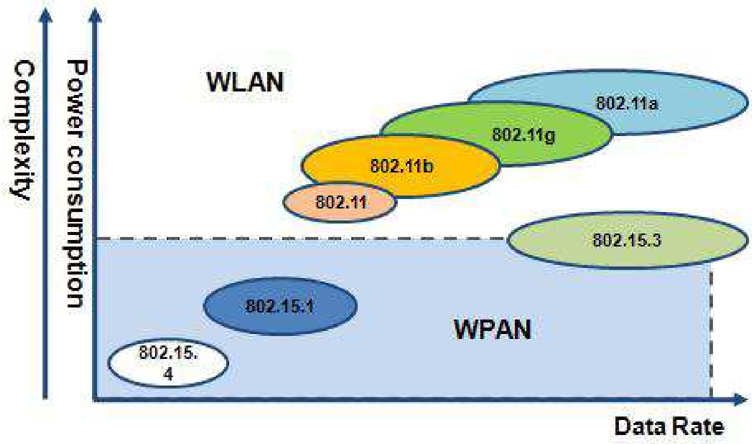


Figure 2.1: The operating space of WPAN standards.

2.2 Wireless Sensor Network

Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate in a short distance [24]. A network that supports the LR-WPAN has been called wireless sensor network (WSN). Sensor networks are composed of a large number of sensor nodes that are densely deployed in a physical space, which is called a sensor field. They monitor physical phenomena, deliver information, and cooperate with neighbor nodes [20, 21, 22, 24, 25]. Figure 2.2 depicts a typical example of wireless sensor networks. Each sensor node has the capabilities to collect data and route data to the sink node. Data are routed to the sink node, which communicates with the Internet, by multi-hop transmission in an infrastructureless area [24]. These sensor nodes should have ad-hoc networking ability, which does not necessitate network infrastructure, to communicate with other nodes. Ad-hoc network schemes cannot be applied directly to sensor networks because sensor networks consist of several nodes and they transmit data using broadcast and data-centric features. There have been numerous studies on efficient rout-

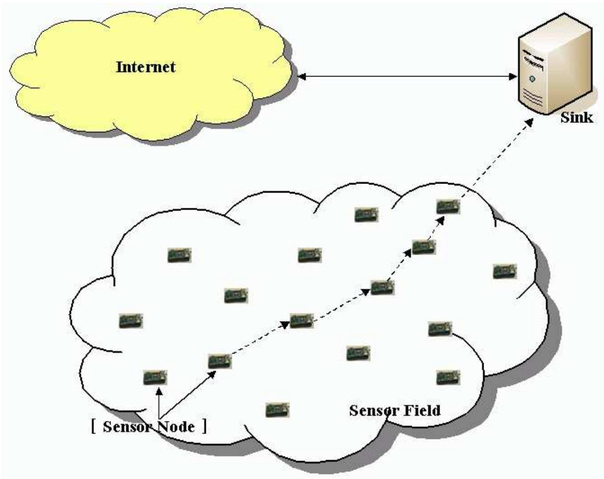


Figure 2.2: Wireless sensor networks.

ing algorithms in wireless sensor networks. A data-centric feature with attribute-based addressing in sensor networks differs from other wireless networks using an IP address. The sink node floods queries which specify the features of required data, then sensor nodes respond if collected data in sensor nodes corresponds with the queries.

For WSN, there are several topics: Node deployment, Clustering, Data transmission, Query processing, Internet connectivity, etc. All of the topics have been studied for energy-efficient WSN because WSN consists of tiny sensor nodes with limited resources. Since wireless communication occupies a large portion of the energy consumption in WSN, data transmission in WSN becomes the major topic. Thus, several kinds of routing scheme for data transmission are presented [26]. In addition, for data transmission in WSN, reliable end-to-end data transmission is desirable because the high packet loss occurs during multi-hop transmissions.

In general, routing protocols for wireless sensor networks are classified into two types: flat routing protocols and hierarchical routing protocols. Flat routing protocols are the same as typical data-centric protocols. Data are requested through queries and the properties of the data are specified by attribute-based addressing. The nodes which receive the query have the same opportunity to transmit data and they route data to the sink node through a multi-hop network. Flat routing protocols as data-centric routing protocols follow the aggregation paradigm, whereby data aggregation is performed at intermediate nodes to reduce the number of data transmissions. Addressing schemes such as attribute-value pairs, however, might not be sufficient for complex queries and they are usually dependent on applications [26]. In addition, all intermediate nodes must decide how long to wait for data from each of their neighbors. Waiting a long time at intermediate nodes results in more data and thus higher accuracy but transmission delay will be increased [1]. We cannot apply the aggregation paradigm to flat routing protocols without determining an optimal waiting time. Since conventional flat routing protocols do not include algorithms for waiting time, excessive traffic is transmitted over flat routing protocols. That is, although flat routing protocols are practical in large scale sensor networks, a large quantity of data is transmitted in flat routing protocols.

In hierarchical routing protocols, sensor nodes in a sensor field construct clusters for routing and then data transmission occurs as two steps, i.e., intra-cluster routing and inter-cluster routing. Since the performance of the hierarchical routing depends on the clustering, the clustering topic is also important for data transmission. The clustering methods in hierarchical routing protocols have been widely used in ad-hoc networks and sensor networks, and there are various algorithms to construct a cluster [2, 3, 4, 5, 6]. By the clustering methods, hierarchical routing protocols can reduce the number of data transmissions. The hierarchical routing protocols, therefore, spend less energy for data communication with the sink node.

Figure 2.3: Wireless body area networks.

2.3 Wireless Body Area Network

A wireless body area network (WBAN), which is a type of WPANs, functions in the vicinity of, on, or inside a human body. It consists of a coordinator, medical devices and non-medical (consumer electronics: CE) devices. Recently, IEEE adopted the WBAN as the next generation of wireless technology for WPANs and the WBAN starts as a task group (TG) of WPANs from November, 2007 [27, 28, 29]. WBAN will mainly be utilized for smart services, including healthcare, and it allows simultaneously both medical and non-medical (CE) applications. The medical and non-medical applications show different characteristics. In general, medical applications include monitoring of biomedical signals, and low rate remote control of medical devices. Non-medical applications include audio, video, and bulk data transfer, etc. In addition, a WBAN provides a flexible data rate of 10Kbps to 10Mbps as well as a very short transmission range of at least 3m with low power. Because of these characteristics, a WBAN is distinguished from existing WPAN technologies.

At initial state of healthcare applications are supported by WSN. In WSN, only controlling and monitoring for the services are available. But, to provide smart services for a human body including the healthcare application, a novel wireless technology is needed.

IEEE 802.15.6 is the WBAN standard and it aims to support the following design aspects: a low complexity, low cost, low power and reliable transmission. It has three types of applications [28, 29]: healthcare, assistance to people with disabilities, and entertainment. Additionally, people may utilize these applications simultaneously. Traffic flow can vary depending on the following applications: point-to-multipoint, multipoint-to-point, and point-to-point. IEEE 802.15.6 allows a 5% packet error rate and a 256 byte payload at very short transmission range with a flexible data rate. It also adopts four channel models among the WBAN devices. In addition, it considers two PHYs to be MICS (Medical Implant Communications Service) and ISM (Industrial Scientific Medical) and supports the periodic traffic and burst traffic for various applications. For Quality of Service (QoS), the latency in medical applications should be less than 125ms and the latency in non-medical applications should be less than 250ms [27].

Until now, monitoring of the human body has been the key technology for WBAN smart services [30, 31, 32]. There are several projects about the u-Healthcare services such as MobiHealth [33], M-health [34], Personal Care Connect [35] and CareNet [36]. These projects collect and analyze medical information from the human body. The projects were developed based on WPAN technologies. Specifically, they only dealt with medical information over networks. The network architectures for the existing WBAN projects are constructed as a two-tier wireless network [33, 34, 35, 36]. The lower tier contains several sensor devices connected to a coordinator and ZigBee or Bluetooth is used for the data transmission. At the higher tier, the coordinator connects with an Internet gateway and wireless local area network (WLAN) or wireless wide area network (WWAN) technology is utilized to communicate with the coordinator with an external server via the Internet. The existing network architectures focus on the status monitoring of an individual WBAN. Thus, sensor devices over network architectures transmit medical information with a low data rate. However, as mentioned previously, WBAN should provide flexible services in both medical and non-medical devices.

Chapter 3

Practical Data Transmission in Cluster-based Sensor Networks

In this chapter, the thesis explains a more accurate computation method for the ratio of cluster-heads by improving the method of Bandyopadhyay et al. [39] and describes a d-hop clustering using the ratio to expand the range of clusters. In addition, the thesis provides multi-hop routing to be used in a POS environment.

3.1 Overview

Cluster-based hierarchical routing algorithms are known to be more efficient than flat routing algorithms in general because only cluster-heads communicate with the sink node. As explained in Section 2.2, a hierarchical routing algorithm consists of two phases: clustering and routing. Sensor nodes select cluster-heads and construct clusters in the clustering phase. The routing phase to transmit data can be divided into two steps: intra-cluster routing and inter-cluster routing. Sensor nodes within a cluster deliver data to their cluster-head in intra-cluster routing step and cluster-heads route data to the sink node in inter-cluster routing step.

In the hierarchical routing, the cluster organization is the most important because the number of clusters and the size of clusters mainly affect the performance. Thus, we first deal with the analysis of the ratio of cluster-heads to obtain more accurate results in Section 3.3. Next, we describe a clustering method using a d-hop approach in

Section 3.4. Amis *et al.* [37] explained how the d-hop approach could improve network performance but they did not indicate how to determine the d value. We propose a method to find the proper d value in our clustering method. In Section 3.5, we present the cluster-head selection algorithm that considers the residual energy and connectivity of a node. Finally, we present the hop-count based multi-hop routing algorithm for intra/inter-cluster routing which considers minimum hop-count and residual energy in Section 3.6.

3.2 Related work

Although cluster-based hierarchical routing algorithms can reduce communication costs compared with flat routing algorithms, communication is still a major power consumption factor in hierarchical routing algorithms. There have been many attempts to reduce communication costs by constructing clusters efficiently.

In the most classical method of constructing clusters, identifications of nodes are used. Each node is identified by a unique integer ID (identification) after deployment. The linked cluster algorithm by Baker selects the highest numbered node as a cluster-head in the mobile ad-hoc network [2]. If there are several nodes outside the region of the highest numbered node N, node $N-1$ becomes a cluster-head. Since the linked cluster algorithm always keeps the highest ID among nodes, each node must know the IDs of other nodes or a centralized node should maintain IDs of all nodes. This method is not appropriate for sensor networks because sensor networks are composed of many sensor nodes and clustering should be done in distributed fashion. In addition, it may not be efficient because sensor networks exploit random IDs for clustering.

When there are a large number of nodes in sensor networks, in general, we can obtain better performance if we utilize the connectivity of each node. Gerla proposed a clustering algorithm using the connectivity of nodes in a mobile ad-hoc network environment

[3]. In this algorithm, a node which has the highest connectivity becomes a cluster-head within a cluster, and if nodes have the same degree of connectivity, a node which has the lowest ID becomes a cluster-head. Because a connectivity-based clustering algorithm must maintain the connectivity values of all nodes, it is not the correct method to use in wireless sensor networks where a large number of sensor nodes are deployed. Furthermore, the connectivity of nodes does not change for a long time because sensor nodes do not move. Thus cluster-heads maintain their roles continuously so that high power consumption occurs at specific nodes which are cluster-heads.

Basagni proposed the Distributed Clustering Algorithm (DCA) which is an advanced method for clustering in a mobile ad-hoc network environment [4]. Every node indicates weight as a measure of its importance and it exchanges messages to get the IDs and weights of its neighbors. Then, nodes which have larger weights perform the roles of cluster-heads. The main advantage of this approach is that it is possible to choose more suitable cluster-heads through a distributed method by considering the importance of nodes as weights. However, DCA does not suggest algorithms to assign weights to nodes.

Because all nodes do not exchange their information with all other nodes in wireless sensor networks, clusters should be constructed with minimum information collected from neighbor nodes. In such wireless sensor networks, the representative hierarchical routing algorithm is 'low-energy adaptive clustering hierarchy' (LEACH) [5] which selects cluster-heads based on a probabilistic method so that energy consumption can be uniformly distributed among nodes. Each member node of a cluster is in single hop distance apart from its cluster-head and cluster-heads directly communicate with the sink node. In the probability-based clustering methods, however, we cannot guarantee that cluster-heads are uniformly distributed in a network field. Although the fraction of nodes that may become cluster-heads is given, it may be impossible to cover all areas of sensor networks with that fraction when we apply POS considered in LR-WPAN as explained in Figure 1.3. In addition, the assumption that every cluster-head directly communicates with the sink node is unrealistic because sensor nodes with restricted resources cannot propagate via radio over 10m in a POS environment.

Hybrid energy-efficient distributed clustering (HEED) improves LEACH by considering the residual energy of each node [6]. That is, it selects the node which has the highest residual energy as a cluster-head. The cluster-head node computes the *Average Minimum Reachability Power* (AMRP) and delivers this AMRP to its neighbor nodes. Neighbor nodes select cluster-heads with lower AMRP. HEED assumes the same energy consumption model as LEACH and tries to maintain the ratio of cluster-heads by changing the transmission radius of nodes. HEED, however, inherits the aforementioned problems of LEACH because it uses the same environment as LEACH. Maintaining the ratio of cluster-heads for clustering through a variable transmission radius is also impossible in a practical POS environment.

While existing hierarchical routing protocols have several constraints in reality because cluster-heads cannot directly transmit data to the faraway sink node, flat routing protocols can be used in real environments since they route data through a multi-hop network. The 'directed diffusion' (DD) [38] protocol is the representative flat routing protocol using data-centric characteristics. In DD, the sink node requests data using query message to sensor nodes then sensor nodes respond if they have the corresponding data. DD has numerous data transmissions in densely deployed sensor networks over a large area. Generally, a sensor node has a correlation with its neighbor nodes regarding sensed data in the local area. Thus there are many nodes with similar data in a dense sensor network and each node with data of interest participates to deliver the data to the sink node. This is the typical weak point of flat routing protocols.

Table 3.2 summarizes the characteristics of the above protocols presented in this section. As we mentioned earlier, compared with flat routing protocols, hierarchical routing protocols show better performance with regard to energy savings. However, in a real environment with IEEE 802.15.4 POS, there are several problems with hierarchical

Table 3.1: Clustering and routing protocols in wireless sensor networks.

	Classification	Clustering	Cluster-head selection	Transmission
D.J.Baker [2]	Hierarchical	Centralized	Identification	Direct
M.Gerla [3]	Hierarchical	Centralized	Connectivity	Direct
S.Basagni [4]	Hierarchical	Distributed	Weight	Direct
LEACH [5]	Hierarchical	Distributed	Probability	Direct
HEED [6]	Hierarchical	Distributed	Residual Energy	Direct
DD [38]	Flat	-	-	Multi-hop
Proposed	Hierarchical	Distributed	Connectivity + Residual Energy	Multi-hop

routing protocols as described in Figure 1.3, because the radio propagation distance of a sensor node is very short and a sensor node has limited energy. First, sensor networks must have more clusters in order to cover all areas of the network field due to the short radio range of a sensor node in POS. Second, cluster-heads cannot transmit data directly over POS.

In the hierarchical sensor networks, to construct clusters in a distributed manner, the ratio of cluster-heads should be given. Bandyopadhyay *et al.* [39] and Chen *et al.* [40] analyzed the ratio but the algorithms from both studies have inaccuracies in the analysis procedure and results. Computation of the ratio by Chen *et al.* resulted in a high ratio of cluster-heads because they do not consider multi-hop communication and POS. Using the high ratio, their scheme constructs many clusters. Bandyopadhyay *et al.* calculated the ratio of cluster-heads using a Poisson point process on a Voronoi tessellation. They modeled total energy cost in sensor networks using multi-hop communication and obtained the ratio of cluster-heads required to minimize the cost. In their calculation of the energy costs of transmitting aggregated data in cluster-heads to the sink node, the authors employed the average distance from all sensor nodes to the sink node. As a result, an inaccurate ratio of cluster-heads was calculated. Furthermore, since Bandyopadhyay *et al.* derived the range of clusters from the inaccurate ratio of cluster-heads, more energy was expended to manage the clusters.

3.3 The ratio of cluster-heads

Both LEACH [5] and HEED [6] suggest that 5% is the ratio of cluster-heads required to build clusters. LEACH obtains this ratio through experimental results and HEED uses the ratio of LEACH. However this ratio is available on the condition of direct communication between cluster-heads and the sink node. To construct clusters efficiently, we need to estimate the ratio of cluster-heads taking multi-hop communication into consideration.

To compute the ratio, we make the following assumptions for a Voronoi tessellation.

- Nodes are distributed according to a homogeneous spatial Poisson process with intensity λ.
- The number of total nodes in a circular area is a Poisson random variable, N with mean λA where A is area.
- Nodes have probability p of becoming a cluster-head.
- A transmission radius of each node is R_t.
- A wireless channel is a free space and error-free.
- Processing energy in a node is not considered.
- A sink node exists in the sensor field.

The network field is divided into several zones called Voronoi cells. Each Voronoi cell consists of a cluster-head and member nodes of the cluster-head. Cluster-heads are denoted as P1 which has the intensity $\lambda_1 = p\lambda$ and non cluster-heads are denoted as P0 which has the intensity $\lambda_0 = (1-p)\lambda$. The intensities are homogeneous spatial Poisson process.

Using Foss [41, 42], we obtain the number of P0 particles (N_c) and the total length of all the segments (L_c) connecting the particles of the P0 to the nucleus P1 in a Voronoi cell when the number of nodes n is given

$$E[N_c|N = n] = \frac{\lambda_0}{\lambda_1} \tag{3.1}$$

$$E[L_c|N = n] = \frac{\lambda_0}{2\lambda_1^{3/2}}. \tag{3.2}$$

These equations are derived by aggregate characteristics (S_f). In a Voronoi cell, an aggregate indicates the phenomenon that P0 particles connect to the nucleus P1 [41, 42]. When we consider a circular cell, the S_f function, which is applied to the Campbell theorem [1] [43] and Palm distribution [2]. [44], can be represented as

$$E[S_f|N = n] = \lambda_0 \int_0^\infty f(l) 2\pi l e^{-\lambda_1 \pi l^2} dl, \tag{3.3}$$

Taking $f(l) = 1$ and $f(l) = l$ we get the expectations of the variables N_c and L_c respectively, where l means the length of each particle. When we define $f(l)$ to describe the hop-count of each particle, we can derive the total hop-count in a Voronoi cell.

The hop-count for each particle depends on l and distances between relay nodes. The distances between relay nodes are determined by positions of relay nodes which are placed in a range of the transmission radius (R_t). For example, in Figure 3.1, the distance r_i

[1] The Campbell theorem represents the number of nodes by density and a deployed area of nodes.

[2] Palm distribution for a node x connecting to the cluster-head $T(0)$ with a radius l: $P\{x \in T(0)\} = e^{-\lambda_1 \pi l^2}$

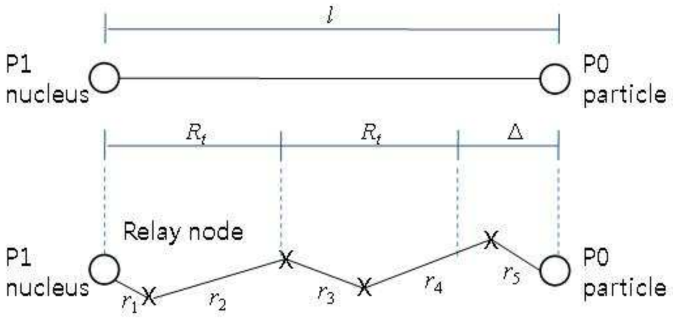


Figure 3.1: Relationship between hop-count and positions of relay nodes.

$(i = 1, 2, \cdots, 5)$ for each hop has a value between 0 and R_t and the P0 particle has 5 hops.

Thus we utilize the mean value of the distance between relay nodes (r). Using l and r of a particle, the hop-count of single particle is depicted as $\lceil \frac{l}{r} \rceil$ and the total hop-count (H_c) in a Voronoi cell is

$$E[H_c|N = n] = \lambda_0 \int_0^\infty \left\lceil \frac{l}{r} \right\rceil 2\pi l e^{-\lambda_1 \pi l^2} dl. \tag{3.4}$$

$\lceil \frac{l}{r} \rceil$ can be represented by $\frac{l}{r} + \alpha$, where α is a value to represent the hop-count with integer $(0 \leq \alpha < 1)$. Then Eq.(3.4) can be

$$\begin{aligned} E[H_c|N = n] &= \lambda_0 \int_0^\infty \left(\frac{l}{r} + \alpha \right) 2\pi l e^{-\lambda_1 \pi l^2} dl. \\ &= \frac{\lambda_0 + 2r\alpha\lambda_0\sqrt{\lambda_1}}{2r\lambda_1^{3/2}}. \end{aligned} \tag{3.5}$$

We now calculate the total energy consumption cost using Eq.(3.5). Then we derive the probability p required to minimize the total energy cost. The total energy consumption in hierarchical sensor networks occurs in two hierarchies on a Voronoi tessellation. In the first hierarchy, we deal with the relation between a cluster-head and its member nodes in a Voronoi cell. In multi-hop transmission, the energy cost is represented by multiplying 1-hop transmission cost and hop-count. When C_{1st} is the energy cost used by the member nodes to transmit data to the cluster-head, the energy cost is

$$\begin{aligned} E[C_{1st}|N=n] &= E[T_{1-hop}] \cdot E[H_c|N=n] \\ &= T_{cost} \cdot \frac{(1-p) + 2r\alpha(1-p)\sqrt{p\lambda}}{2rp^{3/2}\sqrt{\lambda}}, \end{aligned} \tag{3.6}$$

where T_{cost} is the mean value of 1-hop transmission cost $E[T_{1-hop}]$. Since $E[H_c|N=n]$ indicates total hop-count for data transmission of each node in a Voronoi cell, the energy cost in a Voronoi cell is represented by Eq.(3.6).

In the second hierarchy, we consider a sensor field, which consists of several cluster-heads and the sink node, as a large Voronoi cell. Given the number of nodes is n, major factors p' and λ' are

$$p' = \frac{1}{1+np} \tag{3.7}$$

$$\lambda' = \frac{(1+np)\lambda}{n}. \tag{3.8}$$

Then, we can denote H_{CH} as the total hop-count of all segments connecting the cluster-heads to the sink node when $\lambda'_0 = (1-p')\lambda'$ and $\lambda'_1 = p'\lambda'$

$$\begin{aligned} E[H_{CH}|N=n] &= \frac{\lambda'_0 + 2r\alpha\lambda'_0\sqrt{\lambda'_1}}{2r\lambda_1'^{3/2}} \\ &= \frac{(1-p') + 2r\alpha(1-p')\sqrt{p'\lambda'}}{2rp'^{3/2}\sqrt{\lambda'}}. \end{aligned} \tag{3.9}$$

The energy cost in the second hierarchy is computed in the same manner as the first hierarchy

$$\begin{aligned} E[C_{2nd}|N=n] &= T_{cost} \cdot E[H_{CH}|N=n] \\ &= T_{cost} \cdot \frac{\lambda'_0 + 2r\alpha\lambda'_0\sqrt{\lambda'_1}}{2r\lambda_1'^{3/2}} \\ &= T_{cost} \cdot \frac{n^{3/2}p + 2r\alpha np\sqrt{\lambda}}{2r\sqrt{\lambda}}. \end{aligned} \tag{3.10}$$

The total energy consumption cost is the summation of the costs which occur in the first hierarchy and the second hierarchy

$$\begin{aligned} E[C|N=n] &= E[C_{2nd}|N=n] + E[C_{1st}|N=n]\cdot np \\ &= T_{cost}\cdot\left(\frac{n^{3/2}p + 2r\alpha np\sqrt{\lambda}}{2r\sqrt{\lambda}} + \frac{(1-p)+2r\alpha(1-p)\sqrt{p\lambda}}{2rp^{3/2}\sqrt{\lambda}}\cdot np\right). \end{aligned} \tag{3.11}$$

Removing the conditioning on N yields:

$$\begin{aligned} E[C] &= E[E[C|N=n]] \\ &= E[N]\cdot T_{cost}\cdot\left(\frac{E[N]^{1/2}p + 2r\alpha p\sqrt{\lambda}}{2r\sqrt{\lambda}} + \frac{(1-p)+2r\alpha(1-p)\sqrt{p\lambda}}{2r\sqrt{p\lambda}}\right) \\ &= \frac{\lambda A T_{cost}}{2r\sqrt{\lambda}}\cdot\left((\sqrt{\lambda A} + 2r\alpha\sqrt{\lambda})p + \frac{(1-p)+2r\alpha(1-p)\sqrt{p\lambda}}{\sqrt{p}}\right). \end{aligned} \tag{3.12}$$

We can derive the optimal p that minimizes the total energy consumption cost $E[C]$ from Eq.(3.12).

3.4 d-hop clustering

Given the ratio of cluster-heads, clustering should be performed in a distributed manner. This is a major requirement in hierarchical routing protocols. In the proposed clustering algorithm, all nodes do not need to receive the information required for clustering from a particular central node. Rather, each node obtains status information such as the identifier of a node, the strength of power signal, and the ratio of residual energy from neighboring nodes before constructing clusters. The information obtained by this procedure is also used in cluster-head selection and intra/inter-cluster routing.

Figure 3.2 describes the pseudo-code of the proposed clustering algorithm. First, the procedure to scan neighbor nodes is performed. Each node sends an ADV message to neighbor nodes through broadcast using the maximum communication range of a single

Scan Neighbor Nodes

```
Send ADV message to neighbors
if (Receive ADV message)
    Make Neighbor Nodes Table (NNT)
```

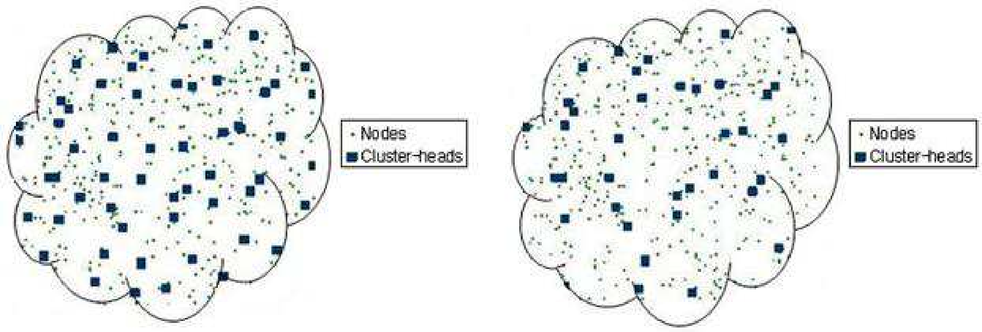
Build Cluster

```
Compute threshold to select a cluster-head
Generate random number R
if (threshold > R)
    Become a cluster-head
    Send CH_STAT message to the members
   (until d-hop range)
    Receive JOIN messages
else
    Not a cluster-head
    if (receive CH_STAT message)
        Send JOIN message
    else
        Become a cluster-head
        Send CH_STAT message to the members
       (until d-hop range)
        Receive JOIN message
```

Figure 3.2: The proposed clustering algorithm.

NID	PW_{signal}	$E_{residual}$	*HID*	HC_{intra}	*SID*	HC_{inter}

Figure 3.3: Neighbor Nodes Table.



(a)The result of 1-hop clustering (b)The result of 3-hop clustering

Figure 3.4: Selected cluster-heads (500 sensor nodes).

hop in order to advertise its status information; it subsequently makes a Neighbor Nodes Table (NNT). The ADV message includes an identifier and the residual energy of a neighbor node. The strength of power signal to deliver data to a neighbor node can be indicated by the strength of the power signal of the received ADV message.

In the proposed hierarchical routing protocol, every node contains an NNT as a routing table. In Figure 3.3, *NID* is an identifier of the sensor node, PW_{signal} is the power strength for transmitting data to a neighbor node, and $E_{residual}$ is the residual energy of a neighbor node *NID*. *HID* is the identifier of a cluster-head, and HC_{intra} is the hop-count from a cluster-head to a current node. *SID* is the identifier of the final destination which denotes the sink node's identifier. HC_{inter} is the hop-count from the sink node to a current node. Each sensor node overwrites NNT periodically and the first three fields are filled through scanning neighbor nodes in the clustering phase. The next two fields (*HID*, HC_{intra}) are filled after deciding on appropriate cluster-heads during the clustering phase and are used in intra-cluster routing. The final two fields (*SID*, HC_{inter}) are filled by the *interest* message broadcasted from the sink node and are used in inter-cluster routing.

Next, the procedure to construct clusters is implemented. Each node generates a random number and computes a threshold which will be explained in Section 3.5. Then, they compare these two values (threshold and random number). If the threshold is larger than the random number, the node becomes a cluster-head. Both LEACH and HEED use this procedure to select cluster-heads. In the proposed algorithm, each selected cluster-head locally broadcasts a CH_STAT message d wireless hops away at most. By doing this, the range of a cluster extends d hops from its cluster-head. The CH_STAT message includes the identifier of the cluster-head and the hop-count from a cluster-head. Other nodes receiving the CH_STAT message, which are not the cluster-head, fill the information from the message into their NNT's and send JOIN messages to participate in the cluster as a member node. If a node does not receive the CH_STAT message, the node becomes a cluster-head and broadcasts its CH_STAT message.

The clustering is performed periodically to balance the energy consumption of sensor nodes. Nevertheless, since traffic of cluster-heads concentrates on the sink node, neighbors of the sink node will rapidly die. Because cluster-heads are selected among other alive nodes in the cluster reconstruction, the area of clusters near the sink node is expanded.

In the process of building clusters, the range of clusters influences the network performance. When d is 1 in the proposed clustering algorithm, lots of clusters are constructed with conventional clustering algorithms. As mentioned in Section 1.2, conventional clustering algorithms which construct clusters with a 1-hop range have numerous clusters to cover the entire area in a real transmission environment. When d is large, fewer clusters are constructed but the load of cluster-heads required to build and manage clusters increases. Hence, hierarchical routing protocols should keep an optimal number of clusters for efficiency. We also need to determine a proper value of d for the proposed clustering algorithm.

Figure 3.4 shows cluster-heads selected for clustering when 500 sensor nodes are deployed. Figure 3.4(a) is the result of 1-hop clustering and Figure 3.4(b) is the result of 3-hop clustering. As shown in Figure 3.4, by expanding a range of clusters, a network can manage the number of clusters. Although the optimal ratio of cluster-heads is given from Section 3.3, many clusters are constructed in a POS environment. In hierarchical sensor networks, it is very important to have an adequate number of clusters to maintain energy efficiency. If an appropriate number of clusters is used, by extending the range of clusters until d-hop, energy consumption for communication in hierarchical sensor networks can be minimized and the network lifetime will increase. Thus, in the proposed clustering algorithm, we find the proper d-hop for a range of clusters given the ratio of clusters (p), the transmission radius (R_t), the number of nodes (N), and the radius of the sensor field (R_v).

Each Voronoi cell has only one P1 nucleus.

$$\pi R_c^2 \lambda_1 = 1, \tag{3.13}$$

where R_c is a radius of the cluster. From Eq.(3.13), R_c can be represented as

$$R_c = \frac{1}{\sqrt{\pi \lambda_1}} = \frac{1}{\sqrt{\pi p \lambda}}. \tag{3.14}$$

As mentioned earlier, the intensity λ is the number of total nodes divided by the area as

$$\lambda = \frac{N}{\pi R_v^2}. \tag{3.15}$$

Then, R_c can be rewritten as

$$R_c = \frac{R_v}{\sqrt{Np}}. \tag{3.16}$$

On the other hand, R_c can be represented by multiplying the mean distance of single hop r and the hop-count of the cluster (d) as depicted in Figure 3.1. Then, the hop-count is

$$d = \left\lceil \frac{R_c}{r} \right\rceil = \left\lceil \frac{R_v}{r\sqrt{Np}} \right\rceil. \tag{3.17}$$

Since r ranges between 0 and R_t, $E[r]$ is $R_t/2$. When R_v, R_t, N, and p are given, the hop-count is calculated as

$$d = \left\lceil \frac{2R_v}{R_t\sqrt{Np}} \right\rceil. \tag{3.18}$$

3.5 Cluster-head selection

In Section 3.4, we mentioned the brief procedure for cluster-head selection to explain the d-hop clustering. In this section, we describe the cluster-head selection algorithm in more detail.

Each sensor node has limited resources in wireless sensor networks and it makes a decision by itself whether it can be a cluster-head. As mentioned earlier, existing hierarchical routing algorithms exploit a probabilistic method to select cluster-heads. In the probabilistic method, the node computes a threshold itself using local information and then it decides whether to be a cluster-head by comparing this threshold with a random number. LEACH [5] has a probabilistic method in which all nodes have the same opportunity to be a cluster-head and HEED [6] adopts a probabilistic method which considers the residual energy of a node for the threshold. In this thesis, we propose a more efficient method than these traditional methods by choosing cluster-heads based on both residual energy and connectivity.

We can obtain the connectivity from the degree of a node. In graph theory, the degree of a node v is the number of edges meeting at v [45]. The number of edges is the same as the number of neighbor nodes within the data transmission range. In addition, the average number of member nodes in a cluster can be represented by

$$N_{cell} = E[N_c]. \tag{3.19}$$

Then we can define the connectivity as the ratio between the average number of member nodes (N_{cell}) and the number of neighbors ($N^i_{neighbor}$) in

$$Connectivity\ of\ node\ i = min\left(\frac{N^i_{neighbor}}{N_{cell}},\ 1\right). \tag{3.20}$$

The energy is represented by the ratio of initial energy to the residual energy of a node. This is used in HEED to consider the residual energy of a node

$$Energy\ of\ node\ i = \frac{E^i_{residual}}{E^i_{init}}. \tag{3.21}$$

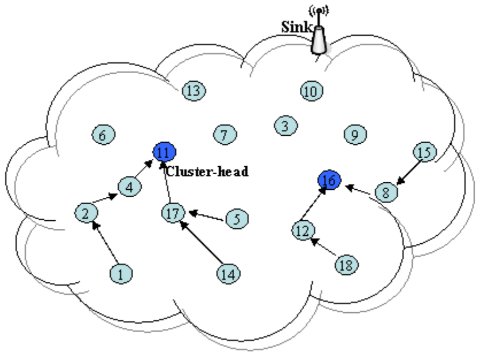
The threshold to become a cluster-head in the proposed algorithm is computed by a multiplication of the connectivity in Eq.(3.20), energy in Eq.(3.21), and p which is used to maintain the desired number of clusters among all sensor nodes

$$T_i = min\left(\frac{N^i_{neighbor}}{N_{cell}},\ 1\right) \cdot \frac{E^i_{residual}}{E^i_{init}} \cdot p. \tag{3.22}$$

After a node computes its threshold, the proposed algorithm applies the threshold to the probabilistic method. The node compares the computed threshold with a random number between 0 and $E^i_{residual}/E^i_{init}$ and then if the threshold is larger, the node becomes a cluster-head.

3.6 Hop-count based routing

After selecting cluster-heads and constructing clusters, intra/inter-cluster routing are required to transmit data to the sink node. The routing algorithm is based on NNT.



NNT

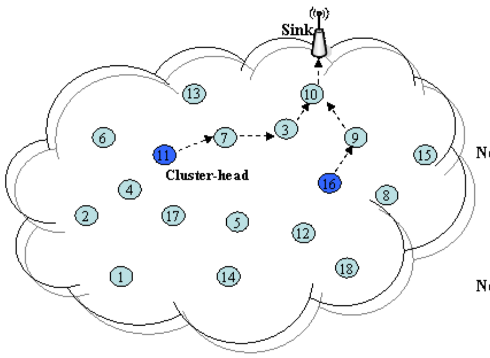
	NID	PW_{signal}	$E_{residual}$	HID	HC_{intra}	SID	HC_{inter}
Node1:	2	20	89	11	2	0	6
Node2:	4	24	65	11	1	0	5
	1	20	91	11	3	0	7
Node4:	11	18	71	11	0	0	4
	17	20	78	11	1	0	5
	2	24	89	11	2	0	6

Figure 3.5: An example of intra-cluster routing.

Every sensor node contains a special data structure NNT as a routing table. The status information of neighbor nodes, identifiers of cluster-heads, and hop-counts from cluster-heads are filled during the clustering phase. In addition, information about the identifier of the sink node and hop-count from the sink node are also filled from the received *interest* message which the sink node broadcasts to the sensor field. After completing NNT, each node routes data through its NNT. Since a node which has fewer hop-counts than a current node is always selected in NNT as the next hop, a routing loop does not occur in the proposed algorithm. NNT is updated periodically when clusters are constructed and the $E_{residual}$ field of NNT can be changed during clustering phases or by receiving information about the change of in the ratio of residual energy of a neighbor node. The intra/inetr-cluster routing using NNT can be performed by time-sharing.

3.6.1 Intra-cluster routing

Sensor nodes use *HID* and HC_{intra} fields in NNT when they communicate with their cluster-head. HC_{intra} contains hop-count information between a cluster-head and its member nodes within the cluster and both *HID* and HC_{intra} are written into NNT when sensor nodes receive the CH_STAT message from other nodes. The CH_STAT messages



NNT

	NID	PW_{signal}	$E_{residual}$	HID	HC_{intra}	SID	HC_{inter}
Node11:	7	19	81	11	1	0	3
	6	17	79	11	1	0	5
	4	18	65	11	1	0	5
	17	16	78	11	1	0	5
Node7:	3	20	80	11	2	0	2
	11	19	71	11	0	0	4
	13	17	68	11	2	0	4
Node3:	10	24	82	16	2	0	1
	7	20	81	11	2	0	2
Node10:	0	18	-	-	-	0	0
	3	24	80	11	2	0	2
	9	20	78	16	1	0	2

Figure 3.6: An example of inter-cluster routing.

are routed until they are d hops away from their cluster-heads and HC_{intra} is incremented by one when they are routed. Sensor nodes receive the CH_STAT messages and update HID and HC_{intra} of the messages to the NNT. Each sensor node looks up its NNT when it transmits data to the neighbor node having the lowest HC_{intra}. If there are several nodes where the lowest HC_{intra} is the same, the nodes deliver data to the neighbor which has the highest $E_{residual}$. In addition, when sensor nodes transmit data, they use PW_{signal} which is obtained during the clustering phase.

Figure 3.5 shows an example of intra-cluster routing. First, node 1 refers to NNT to find node 2 which has the lowest HC_{intra} from itself to a cluster-head. Node 2 performs the same operation and delivers data to node 4. Finally, node 4 transmits data to its cluster-heads.

3.6.2 Inter-cluster routing

As mentioned earlier, cluster-heads deliver data to the sink node directly in conventional routing protocols. However, this is not possible when we consider a practical transmission radius for sensor nodes. Cluster-heads should route data by multi-hop routing through other sensor nodes. Thus, we use the hop-count based inter-cluster routing algorithm, which is the same as intra-cluster routing except for referenced fields in NNT, to transmit data to the sink node. In inter-cluster routing, HC_{inter}, which is the hop-count information from the sink node to a current node, is needed; we get this information from the *interest* message. When sensor nodes receive the *interest* message, the nodes know the identifier of the sink node and HC_{inter}, which is incremented by one when the *interest* message is delivered from the sink node, and the last two fields of NNT are updated. The proposed inter-cluster routing algorithm is similar to intra-cluster routing except that cluster-heads use *SID* and HC_{inter} instead of *HID* and HC_{intra} as routing information.

Figure 3.6 is an example of inter-cluster routing. Data from the cluster-head, node 11, are transmitted in the following sequences in the same way: node 11, node 7, node 3, node 10, and the sink node. The final node 10 checks whether *SID* is *NID* or not and sends data to the sink node if they are equal to each other.

3.7 Performance evaluation

3.7.1 Performance metrics

Our proposed hierarchical routing algorithm aims at efficient operation in a real environment. We develop new performance metrics that reflects the practical sensor network environment. Based on a combination of our performance metrics and traditional metrics, we compare the performance of our proposed algorithm with the existing hierarchical algorithms.

Traditional measurements employ ‘first node die’ (FND) and ‘last node die’ (LND) metrics. FND is the network lifetime to present the degree of load balance about energy consumption. LND indicates the general network lifetime. However, data transmission to the sink node should be done using multi-hop routing in practical wireless sensor networks. Thus, when all the relay nodes near the sink node die, cluster-heads in hierarchical sensor networks cannot deliver data to the sink node. So, it is meaningless to measure LND in a real environment. In this thesis, we define another metric ‘connection nodes die’ (CND) which is the amount of time that neighbor nodes (connection nodes) of the sink node are alive to make connections between cluster-heads and the sink node. If all connection nodes die, the sink node cannot receive sensor data from the network field. We use CND and FND for performance metrics. To represent these metrics in the simulation, *round* is used which is a popular unit for a network lifetime in hierarchical sensor networks. The *round* consists of a set-up phase to organize the clusters and a steady-state phase in which data gathering of the sink node occurs several times [5].

3.7.2 Simulation environments

In the previous section, we proposed a practical algorithm for clustering and routing. Now, we evaluate the performance of our algorithm and compare it with those of LEACH [5], HEED [6], Bandyopadhyay *et al.* [39], and Chen *et al.* [40] through extensive simulations. Both LEACH and HEED are representative hierarchical routing algorithms and the algorithms of both Bandyopadhyay *et al.* and Chen *et al.* provide the ratio of cluster-heads which should be used in hierarchical routing algorithms. However, since the algorithms cannot be directly compared with the proposed algorithm in a practical environment, we partially modify them.

Because cluster-heads in conventional hierarchical routing algorithms cannot communicate directly with the sink node, we modify them so that they deliver data using our NNT as a routing table. Member nodes of each cluster using existing algorithms trans-

Table 3.2: Parameters for performance evaluation.

Parameters	Value
Radius of the network field R_v	50m
Data packet size	100 bytes
Query packet size	25 bytes
Header packet size	25 bytes
E_{elec}	50 nJ/bit
E_{amp}	10 $pJ/bit/m^2$
E_{init}	1 J
Position of the sink node	Center of the network field
# of data gathering of the sink node in a *round*	5
Transmission radius of a node R_t	10 m

mit data to their cluster-heads directly in intra-cluster routing because the algorithms construct clusters with a single hop range. Cluster-heads route data to the sink node by referencing NNT in inter-cluster routing. We define *LEACH2* as modified LEACH and *HEED2* as modified HEED. Similarly we define *BAND2* as a modified scheme of Bandyopadhyay *et al.* and *CHEN2* as Chen *et al.*'s modified scheme. Since Bandyopadhyay *et al.* and Chen *et al.* have no cluster-head selection and data routing schemes, we apply our cluster-head selection and data routing to them. In addition, since Bandyopadhyay *et al.*'s method extends a cluster's range but Chen *et al.*'s method does not, we apply our d-hop computation method to *CHEN2*. For simplicity, we assume an error free wireless environment and randomly distributed sensor nodes in the network field.

In the experiment, we set the number of sensor nodes in a network to 300 and 500. Sensor nodes are deployed in the circular area with 50m radius and the sink node is

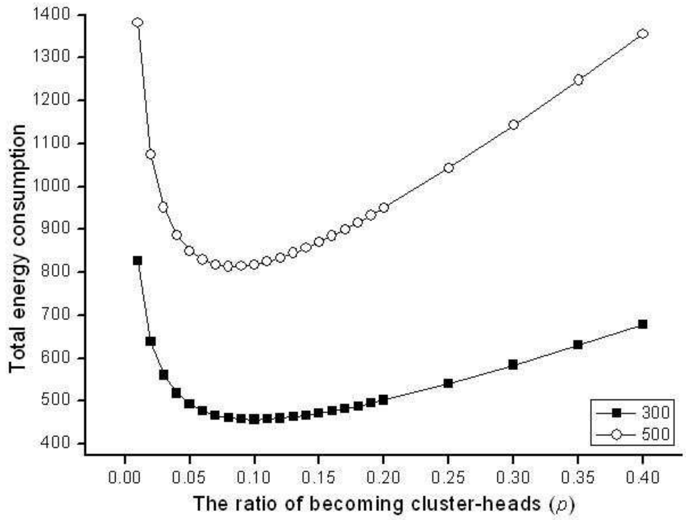


Figure 3.7: Total energy consumption following the ratio of becoming cluster-heads.

placed at the center of the network field. Each sensor node has 1 joule as its initial energy and 10m as its maximum transmission distance. We employ LEACH's radio model as an energy consumption model for data transmission. Using LEACH's radio model, to transmit k-bit message for distance s, the radio of sender expends $(E_{elec}*k+E_{amp}*k*s^2)$J and the radio of receiver expends $(E_{elec} * k)$J [5]. Basic environment parameters are the same as HEED [6].

3.7.3 Simulation results

First, the ratio p of cluster-heads is estimated to compare algorithms. From Eq.(3.12), we obtain the ratio p as 0.0837 for 500-nodes and 0.1003 for 300-nodes. From Figure 3.7, it is clear that these ratios minimize energy expenditure on data communication.

Given the ratio p, the number of nodes N, the transmission radius R_t, and the radius of the sensor field R_v, we can determine the proper d-hop for a range of clusters to maintain the proper number of clusters for the ratio p.

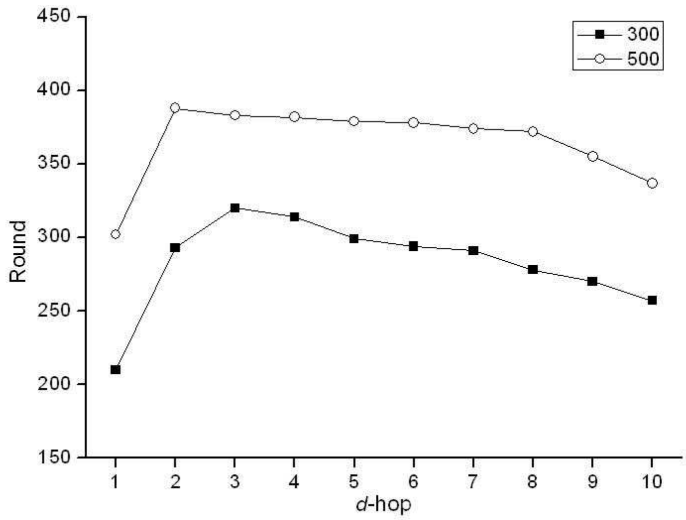


Figure 3.8: Network lifetime (FND) while varying d-hop values.

Figure 3.8 presents the performance variation of our hierarchical routing algorithm according to varying d-hop values. When R_v is 50m and p is 10% and 8.37% for 300 and 500 nodes, respectively, Eq.(3.18) computes d-hop values of 3 and 3, respectively. In the simulation, sensor nodes and cluster-heads are randomly distributed. Nevertheless the d-hop values in Figure 3.8 are equivalent to Eq.(3.18). This shows the d-hop computation can be applied to the real environment.

Hierarchical routing algorithms employ parameters such as the ratio of cluster-heads (p) and d-hop for the range of clusters in Table 3.3 as major factors for simulation. The factors p and d of *Proposed* are calculated by Eq.(3.12) and Eq.(3.18). *LEACH2* and *HEED2* get them from LEACH and HEED. *BAND2* obtains p and d from Bandyopadhyay *et al.* However, *CHEN2* gets only p from Chen *et al.* Thus we calculate d from p in *CHEN2* through Eq.(3.18).

Table 3.4 compares the average number of cluster-heads required for hierarchical routing algorithms. In the case of *Proposed* and *BAND2* which expand the range of

Table 3.3: System parameters for simulation.

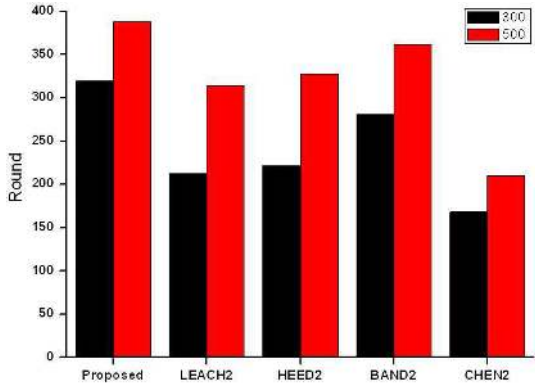
	300 nodes		500 nodes	
	p	d	p	d
Proposed	0.1003	3	0.0837	2
LEACH2	0.05	1	0.05	1
HEED2	0.05	1	0.05	1
BAND2	0.1214	5	0.1012	4
CHEN2	0.276	2	0.232	2

Table 3.4: Average number of cluster-heads on hierarchical routing algorithms.

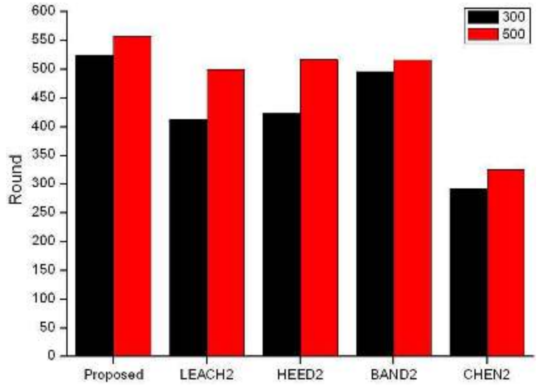
	300 nodes	500 nodes
Proposed	30.4	43.1
LEACH2	49	53.3
HEED2	48.3	50.4
BAND2	33.7	48.5
CHEN2	76.8	110.7

clusters, fewer clusters are made and they maintain clusters with the ratio p. In contrast, for *LEACH2* and *HEED2*, although we set $p = 5\%$, many clusters are constructed and the ratio of cluster-heads has values greater than 5%. Since sensor nodes have a short transmission range in a real environment, clusters constructed with a single hop range cannot cover the entire sensor field. To cover the whole area, more clusters are required. In addition, *CHEN2*, which has a high p ratio constructs numerous clusters.

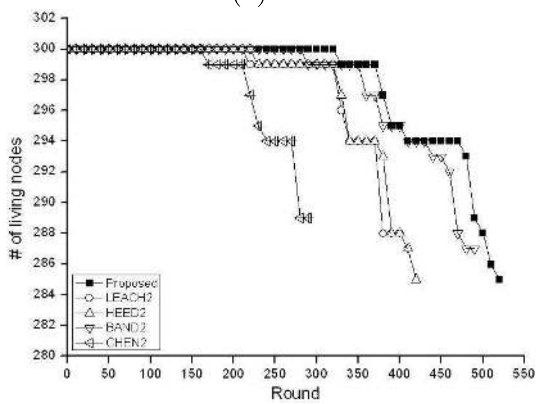
Figure 3.9 illustrates a network lifetime of hierarchical routing algorithms when the number of nodes is 300 and 500. Among the algorithms, *Proposed* and *BAND2* have a longer network lifetime based on both FND and CND metrics because they maintain the



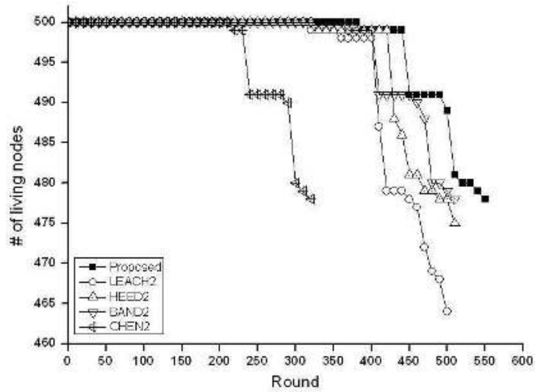
(a) FND



(b) CND



(c) Change of # of living nodes: N=300



(d) Change of # of living nodes: N=500

Figure 3.9: Performance comparison: Network lifetime.

number of clusters as the given ratio of cluster-heads for the clustering by expanding the ragne of clusters until d-hop. *Proposed*, however, is more efficient than *BAND2* because *Proposed* exploits the more accurate ratio of cluster-heads (p) and d-hop to organize clusters than BAND2 as mentioned in Section 3.3 and Section 3.4. The proposed algorithm not only provides the longest FND and CND but also maximizes the number of living nodes as shown in Figure 3.9(c),(d). This is because *Proposed* maintains the optimal number of clusters to minimize energy consumption.

Table 3.5 presents collected data at the sink node during CND. It is straightforward

Table 3.5: Amount of collected data.

	during its lifetime		per *round*	
	300 nodes	500 nodes	300 nodes	500 nodes
Proposed	782989	1388722	1491.4	2488.7
LEACH2	616738	1239341	1493.3	2478.7
HEED2	632723	1283937	1492.3	2483.4
BAND2	740126	1284507	1492.2	2489.3
CHEN2	438118	809072	1495.3	2489.4

that the amount of collected data per *round* is similar in all algorithms because they can deliver all the data during their lifetime. Since CND is the network lifetime during which the sink node can receive data from the sensor field, longer CND indicates the sink node can collect more data. This is the reason why we have presented CND in this thesis. As shown in Figure 3.9 and Table 3.5, the amount of collected data increases proportionally to CND.

3.8 Summary

In a practical sensor network environment, sensor nodes have a limited radio transmission radius. Because existing hierarchical routing algorithms have assumed that data transmission from cluster-heads to the sink node and from sensor nodes to their cluster-heads can be done in one hop, we cannot adopt the algorithms to a real environment. Therefore, in this paper, we have proposed a practical algorithm for clustering and routing in hierarchical sensor networks. The proposed algorithm is efficient because of the following features. It provides the optimal ratio of cluster-heads for the clustering. It maintains an appropriate number of clusters using d-hop approach and it considers residual energy and connectivity of sensor nodes to elect cluster-heads. In addition, to efficiently route sensor data, it is energy-aware for multi-hop routing. From our analysis, the optimal ratio of cluster-heads and the appropriate d-hop among the above features have extremely affected the performance improvement.

Experimental results have validated that the proposed algorithm can improve the network lifetime as much as 27.1% (number of nodes=300), 11.6% (number of nodes=500) for the case of CND compared with *LEACH2*. We can gather as much as 26.9% (number of nodes=300) or 12.1% (number of nodes=500) more data in the sink node compared to *LEACH2* or *HEED2*. In a practical sensor network environment, therefore, the proposed algorithm is the best candidate for clustering and routing algorithms.

Chapter 4

Reliable Data Transmission in Wireless Sensor Networks

In this chapter, the thesis proposes a transmission method to guarantee desired communication reliability of applications. In addition, the thesis provides an efficient buffer management technique which is operated over the proposed transmission method for reliable transmission.

4.1 Overview

Wireless channel of WSN shows high error rate and it accumulates exponentially over multi-hops [11]. Several mechanisms to overcome packet losses over the harsh channel was proposed: *end-to-end* loss recovery (E2E) and *hop-by-hop* loss recovery (HBH) [11, 12]. Since E2E causes long end-to-end delays and frequent transmission failures, HBH was suggested as an alternative. However, HBH shows high memory requirements and considers only 100% reliability. Because data traffic on WSN requires a variety of levels of *communication reliability* (*CR*) depending on the application, a novel loss recovery method to guarantee the desired *CR* should be provided. This thesis proposes the novel flexible loss recovery mechanism that caches data packets intermediate nodes calculated by *CR*.

Tiny sensor nodes have limited memory storages. If there are not data packets for recovery in a buffer, reliable transmission cannot be served. For reliable transmission, the loss recovery mechanism is provided together with a buffer management technique. This thesis also proposes a buffer management technique that precisely calculates how long packets need to be buffered in an intermediate nodes before they can be safely removed. Therefore, data packets are buffered an appropriate amount of time, referred to as *packet holding time*.

4.2 Related work

4.2.1 Existing loss recovery mechanisms

Data communication of sensor networks depends on multi-hop transmission. Since environments of sensor networks usually have harsh wireless channel and channel error accumulates exponentially over multi-hops, high packet loss occurs [11]. In addition, accurate and timely information is crucial for sensor network services such as emergency detection applications. Thus, reliable transmission of the information from sensor nodes to the sink node is essential.

For the reliable transmission, sensor networks employ loss recovery mechanisms. Two types of retransmission have been proposed for the recovery, namely *end-to-end* loss recovery and *hop-by-hop* loss recovery. In these mechanisms, lost packets are retransmitted from a source node or an intermediate node. If a retransmit request for lost packets is sent to a source node, the end-to-end delay may increase because multiple hops from source nodes to the sink node cause high channel error. The well-known HBH mechanisms are PSFQ [11] and RMST [12]. PSFQ is based on ACK message and RMST is on NACK message. In HBH, when intermediate nodes cache data packets into storage, retransmissions can be requested to an intermediate relay node to reduce end-to-end delays. Because sensor nodes have limited resources, however, it is difficult for all sensor nodes to find sufficient space in their routing paths to cache data packets. There is therefore a tradeoff between end-to-end delays and memory requirements.

4.2.2 Existing buffer management techniques

As mentioned earlier, sensor networks should consider an efficient buffer management although a loss recovery mechanism is provided for reliable transmission. Since tiny sensor nodes have limited power and memory, if sensor nodes do not manage their buffers efficiently, buffer overflow can occur. The buffer overflow injures the reliable transmission because the discarded packets by the buffer overflow cannot retransmit for recovery of lost packets during transmission.

Xiao *et al.* [46] proposed a method based on round trip time (RTT), where sensor nodes cache data packets in their buffers until no retransmission request is received for some period of time. The time period depends on the maximum RTT. Another method proposed by Paek and Govidan [47] uses a feedback message with a cumulative ACK sequence, which is the last continuous sequence number of the received packets. A node that receives the feedback message can safely remove packets in its buffer based on the ACK sequence. The RTT-based method requires sensor nodes to maintain the cached packets for a long period of time, while the feedback-based method causes higher energy consumption due to additional messages required for lost packets.

4.3 The flexible loss recovery mechanism: Active Caching

As mentioned previously, E2E involves large end-to-end delays for 100% reliability because of high packet loss during multi-hop transmissions. To guarantee high reliability and minimal end-to-end delays, HBH caches data in every node over a routing path resulting in large memory requirements. When only some nodes cache data on a routing path, there exists a tradeoff between the end-to-end delays and the memory requirements. For applications which do not require 100% reliability, every node needs not cache data via HBH. When a target CR is given, we need a flexible method to guarantee the given CR while minimizing the memory requirement. In this section, we present such a method

- *Active Caching* (AC).

The proposed scheme allows various CRs of application services. It determines positions where data caching occurs using a dynamic programming algorithm, which solves every subproblem just once and then saves its answer in a table to avoid the work of recomputing the answer [48]. If there are holes in sequence numbers of received data, a caching node recognizes packet loss [1]. The caching node sends a NACK message to a previous caching node along the path and the previous caching node retransmits lost packets selectively.

First, we define the problem and subproblems for the active caching as a dynamic programming algorithm to guarantee an end-to-end reliable data transmission as:

Problem: $P_{tx}(H) > CR$.
Subproblem: $P_{tx}(h) > CR$, where $h = 1, 2, \cdots, H$.

The packet delivery rate $P_{tx}(H)$ during total hop counts H should be greater than the desired communication reliability CR. To do that, the packet delivery rate $P_{tx}(h)$ during hop counts h in each hop should be greater than the CR. The key idea for solving the problem is to cache data packets if the probability of packet transmission does not satisfy the desired communication reliability. By solving the subproblems, we can solve the entire problem.

Figure 4.1 shows the proposed active caching algorithm for loss recovery. Each node solves the subproblem using the tables for the packet delivery rate $P_{tx}(i)$ until i-th hop and the caching flag of i-th node $F(i)$. Both $P_{tx}(i-1)$ and $F(i-1)$ of the tables are piggybacked in data packets and they are delivered to the next node. In a source node ($i = 1$), $P_{tx}(1)$ is $1 - p_1$ as the packet delivery rate at the 1st hop and $F(1)$ is $true$. *Line 1-3:* n_i calculates $P_{tx}(i)$ using $P_{tx}(i-1)$, where $P_{tx}(i)$ accumulates the packet delivery rate $1 - p_i$ of i-th hop while packets are transmitted. After that, it compares $P_{tx}(i)$ with CR. If $P_{tx}(i)$ satisfies the desired CR, n_i is not a caching node ($F(i)$ is $false$). *Line 4-6:*

$RELIABLE-TRANSMIT(CR, i, P_{tx}(i-1), F(i-1))$

$P_{tx}[i] \leftarrow P_{tx}[i-1] \cdot (1-p_i)$
if $P_{tx}[i] > CR$
    then $F[i] \leftarrow false$
    else $F[i] \leftarrow true$
        $P_{tx}[i] \leftarrow 1 \cdot (1-p_i)$
        cache data packets to a node n_i
forward $P_{tx}[i]$ and $F[i]$ to the next node

Figure 4.1: Active caching algorithm at i-th node, n_i.

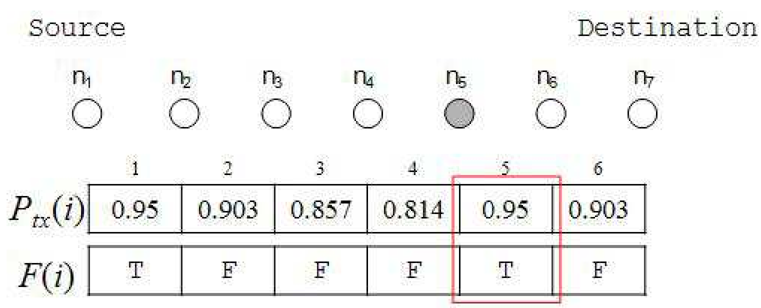


Figure 4.2: An example of active caching.

If $P_{tx}(i)$ does not guarantee the desired CR, n_i becomes a caching node ($F(i)$ is $true$). In this case, $P_{tx}(i)$ compensates for its packet delivery rate as the reliability instead of accumulating $P_{tx}(i)$ and data packets are cached onto n_i's buffer. Each node runs the algorithm of Figure 4.1 and the total active caching over a routing path is performed by the dynamic programming algorithm. Figure 4.2 shows an example of the active caching when seven sensor nodes are deployed sequentially and they have an average 5% packet loss rate and 80% CR. Every node satisfies 80% CR and data caching occurs at n_5. When packet loss happens between a source node n_1 and the caching node n_5, the caching node requests retransmission to the source node. When packet loss happens between the caching node and a destination node n_7, the destination node requests retransmission to the caching node.

4.4 Analysis

A packet loss rate occurs due to wireless link and contention errors. Since all the packets are destined to the sink node in wireless sensor networks, the contention error in links close to the sink node may increase. To model the packet loss rate at i-th hop, we assume the uniform link error p_l and the contention error which is proportional to the square of transmission hop counts.

$$p_i = p_l + \delta i^2, \tag{4.1}$$

where δ is the contention failure factor. Then the packet delivery rate during h hops from the s-th node is

$$P_{tx}(s,h) = \prod_{i=s}^{s+h-1} (1 - p_i). \tag{4.2}$$

Data caching occurs when $P_{tx}(s,h)$ is lower than CR. When the number of nodes N over a route and CR are given, the hop counts h from a caching node s and the number of caching nodes N_ϵ are obtained by the function in Figure 4.3. Φ represents a set of

$CalcHopCounts(N, CR)$

$n \leftarrow 1,\ s \leftarrow 1,\ h \leftarrow 1, N_c \leftarrow 0$

$\Phi = \phi$

loop: $n < N$

  if $P_{tx}(s, h) > CR$

    then $n \leftarrow n + 1, h \leftarrow h + 1$ //no caching

    else $h \leftarrow h - 1$ //caching

      if $(h = 0)$

        then $h \leftarrow 1, n \leftarrow n + 1$

      add (s, h) to Φ, $N_\epsilon \leftarrow N_\epsilon + 1$

      $s \leftarrow n,\ h \leftarrow 1$

end loop

if $(h > 1)$

  then add $(s, h - 1)$ to Φ, $N_\epsilon \leftarrow N_\epsilon + 1$

Figure 4.3: Function to obtain (s, h) tuples.

(s, h) tuples and the (s, h) tuples are used to compute the retransmission counts of lost packets. For example in Figure 4.2, $\Phi = \{(1, 4), (5, 2)\}$.

$$\Phi = \{(s_j, h_j) \mid j = 1, \cdots, N_\epsilon\}. \tag{4.3}$$

If the retransmission counts for h hops from a caching node s is given by $\psi(s, h)$, the total retransmission counts $E[\tau]$ between a source node and a sink node are represented by the sum of $\psi(s, h)$ as

$$E[\tau] = \sum_{j=1}^{N_c} \psi(s_j, h_j). \tag{4.4}$$

Because the retransmitted packets can also experience transmission failure, we should consider repeated retransmissions for $\psi(s, h)$. Let $\Gamma_f(j, s, h)$ indicate the number of transmitted packets at the j-th retransmission. Then $\psi(s, h)$ can be represented as

$$\psi(s, h) = \sum_{j=1}^{\infty} \big(h \cdot \Gamma_f(j, s, h) \cdot P_{tx}(s, h)\big). \tag{4.5}$$

If we let $\Gamma_s(k, s, h)$ be the number of successfully transmitted packets among k packets during h hops from node s, $\Gamma_f(j, s, h)$ can be represented recursively as

$$\Gamma_f(j, s, h) = \Gamma_f(j-1, s, h) - \big[\Gamma_s\big(\Gamma_f(j-1, s, h), s, h\big)\big], \tag{4.6}$$

where $\Gamma_f(0, s, h) = K$ and K is the number of total packets which is generated in a source node ($[x]$ is n, in case of $n - 0.5 \leq x < n + 0.5$).

The number of successfully transmitted packets $\Gamma_s(k, s, h)$ can be calculated by the probability of successful transmission of Bernoulli trials $P_s(k, m, s, h)$ as

$$\Gamma_s(k, s, h) = \sum_{m=1}^{k} m \cdot P_s(k, m, s, h). \tag{4.7}$$

If m data packets are transmitted successfully among k packets to deliver across h hops from a caching node s, the probability of successful transmissions can be obtained by Bernoulli trials as

$$P_s(k, m, s, h) = \binom{k}{m} \cdot P_{tx}(s, h)^m \cdot \big(1 - P_{tx}(s, h)\big)^{k-m}. \tag{4.8}$$

The memory requirement B is defined as the caching rates of intermediate nodes including a source node. It is computed by N_ϵ and the number of relay nodes over a routing path:

$$E[B] = \frac{N_\epsilon}{N-1}. \tag{4.9}$$

A high $E[\tau]$ indicates large end-to-end transmission delays and $E[B]$ represents the memory requirements of buffers on the data transmission routes. Because both $E[\tau]$ and $E[B]$ can be estimated by CR of traffic through Eq.(4.4) and Eq.(4.9), a flexible data transmission system can be designed.

4.5 The proposed buffer management technique

The proposed buffer management technique estimates the packet holding time based on the number of data transmissions. The estimated transmission counts also include the number of retransmissions for lost packets, which can be calculated using the analysis presented in Section 4.4. When a source node transmits k data packets through h hops, the transmission counts will be kh assuming there are no transmission failures. When packet losses occur, the transmission count can be estimated by adding the retransmission count for the lost packets to kh. The lost packets during a multi-hop communication are continually retransmitted until they all arrive at the next data caching node.

The $P_{tx}(s, h)$ can be applied to Active Caching in order to obtain the hop-count h from node s to the next caching node. Given a level of CR for an application data, node s obtains h using the $HopCount(CR)$ function given in Fig. 4.4.

Once h is obtained, the number of successfully transmitted packets among k packets can be obtained by $\Gamma_s(k, s, h)$ of Eq.(4.7).

Then, the number of retransmitted packets γ and the number of retransmission request messages ν can be obtained using the $GetReTxCounts(K, s, h)$ function in Fig. 4.5, where K is the total number of data packets.

$HopCount(CR)$

$h \leftarrow 1$

loop: $P_d(s, h) > CR$

  $h \leftarrow h + 1$

end loop

Figure 4.4: Function to obtain the hop-count h for the next caching node.

$GetReTxCounts(K, s, h)$

$k \leftarrow K$, $packets \leftarrow 0$

$\gamma \leftarrow 0$, $\nu \leftarrow 0$, $success \leftarrow 0$

loop: $packets < K$

  $success \leftarrow [\Gamma_s(k, s, h)]$

  $packets \leftarrow packets + success$

  If $packets < K$

    $\nu \leftarrow \nu + 1$

    $k \leftarrow k - success$

    $\gamma \leftarrow k \times h + \gamma$

end loop

Figure 4.5: Function to obtain the number of retransmitted packets and retransmission request messages.

After γ and ν are obtained, the node can estimate the packet holding time, T_b, given as

$$T_b = \frac{(Kh + \gamma + \nu h) \cdot S}{R}, \tag{4.10}$$

where S is the size of a single packet and R is the transmission rate. $GetReTxCounts(K, s, h)$ considers all possible retransmissions needed to deliver all the packets. Thus, T_b represents the worst-case transmission time for all the data packets. Therefore, the cached data packets will not be removed before the retransmissions for lost packets are completed.

Based on the above analysis, each caching node over a routing path buffers data packets for T_b to guarantee communication reliability with efficient memory usage. In addition, the proposed buffer management technique can also be applied to both end-to-end and hop-by-hop loss recovery schemes. For an end-to-end loss recovery scheme, T_b at the source node is calculated using the hop-count from the source node to the destination node, i.e., h. Similarly, for a hop-by-hop loss recovery scheme, T_b at each intermediate node is calculated based on $h = 1$.

4.6 Performance evaluation

4.6.1 Evaluation for the proposed loss recovery

In this section, we validate the analysis through simulations and compare the performance of *Active Caching* (AC) with that of E2E and HBH. For the simulation, we assume 20 sensor nodes are deployed sequentially and the wireless channel has both link and contention error as described in Section 4.4. The contention failure factor δ is determined as 0.0001 by considering total hop counts. So, p_i in Eq.(1) ranges from 0.03 to 0.07 when p_l is 0.03 in our experiments. The sensor nodes employ AODV as a routing protocol. Assuming a packet is 30bytes and the data rate is 250kbps, we perform the analysis and

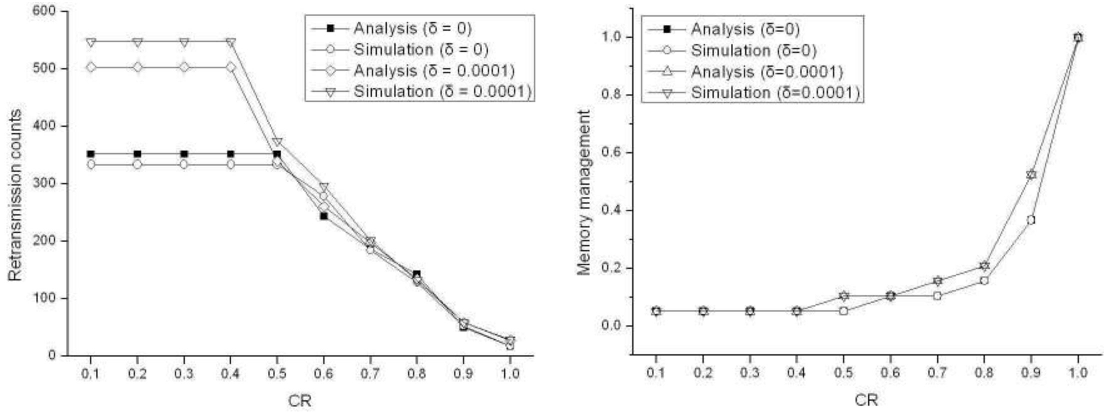


Figure 4.6: Validation of our analysis (p_l=0.03).

simulation by varying CR from 10% to 100%. AC with CR from 0.1 to 1 is expressed as AC0.1 to AC1.

Figure 4.6 shows the results of the analysis and the simulation of the retransmission counts and the memory requirements when a source transmits 40 packets. The results of the analysis and the simulation show an average of 94% similarity. Figure 4.6 also represents the tradeoff as mentioned earlier. The high CR requires a high memory requirement for reliability and it decreases the retransmission counts. When the memory requirement is the lowest, the retransmission counts are the highest and AC runs as E2E. In short, we can design wireless sensor networks that take the desired CR and memory requirements into consideration through the proposed active caching.

Figure 4.7 shows the performance comparison of E2E, HBH, and AC. Because AC with the highest memory requirement caches data to every intermediate node, it operates as HBH. When AC does not perform data caching, it operates as E2E. That is, AC switches between HBH and E2E while showing the performance tradeoff between them. In addition, it has a tolerable end-to-end delay to minimize the memory requirement depending on CR. In Figure 4.7, the end-to-end delays of E2E increase when the wireless channel has a high link error rate. However, the end-to-end delay of AC maintains similar

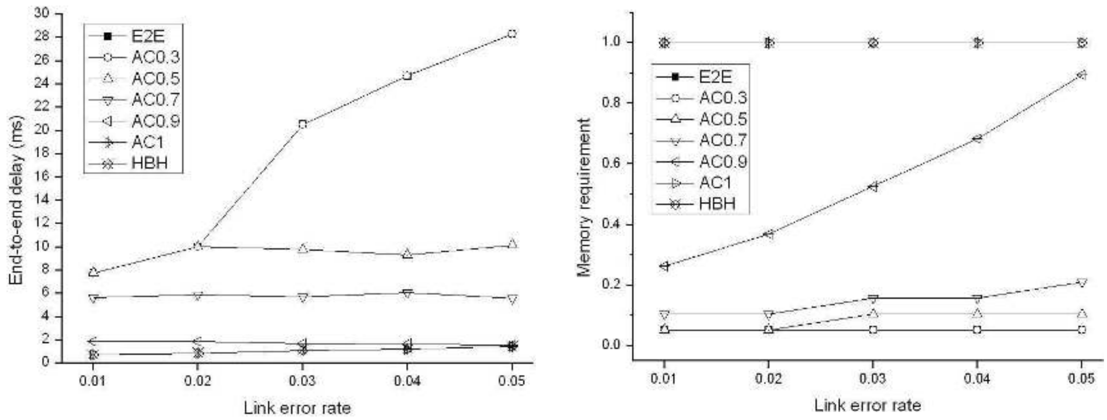


Figure 4.7: Performance comparison of E2E, HBH, and AC.

values because AC increases the memory requirements to ensure CR. An evaluation has been performed for 10 and 50 nodes deployed over a route, and the results are similar to the case of 20 nodes. These results have been omitted due to the page limitation.

Figure 4.8 shows the ratio of caching nodes over relay nodes. Because the contention error increases when the density of nodes increases, the ratio of caching nodes increases when the number of sensor nodes increases.

4.6.2 Evaluation for the proposed buffer management

This section discusses the simulation environment and evaluates the performance of the proposed buffer management technique. The simulated WSN consists of 300 homogeneous sensor nodes and operates under IEEE 802.15.4. Ten source nodes which are chosen randomly generate event data. *Active Caching* (AC) is used to provide reliable end-to-end transmissions with CR values of 80% to 100%. We assume the source nodes generate events with the Poisson distribution, and each event consists of 20 packets with the packet size of 30bytes. In addition, wireless channel with transmission rates of 250kbps has both link and contention error as described in Section 4.4. The contention failure factor δ is determined as 0.0002 by considering total hop counts and p_i ranges

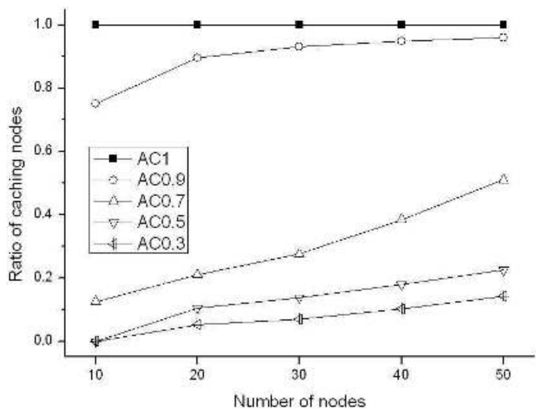


Figure 4.8: The ratio of caching nodes.

from 0.03 to 0.05 when p_l is 0.03. The simulator was implemented with SMPL library [49], which is a C language based event-driven simulator.

The proposed method is compared with the RTT-based method presented in [46] and the feedback-based method presented in [47] in terms of average buffer requirements and energy consumption. Xiao *et al.* [46] employed round trip time (RTT) to determine the packet holding times. Paek and Govidan [47] exploited additional feedback messages with cumulative ACK sequences to remove data packets in a buffer.

Figure 4.9 shows the packet holding time of the proposed buffer management and the existing methods [46, 47] for different CR values. Both the proposed technique and the feedback-based method have significantly shorter packet holding time than the RTT-based method and are even shorter than one RTT. The feedback-based method needs slight longer packet holding time than the proposed one because it includes additional messages. In contrast, caching nodes in the RTT-based method perform retransmissions for lost packets within the first RTT and then they wait for second RTT to remove the cached packets from their buffers.

When a node receives data packets with a high CR, they are maintained in its buffer

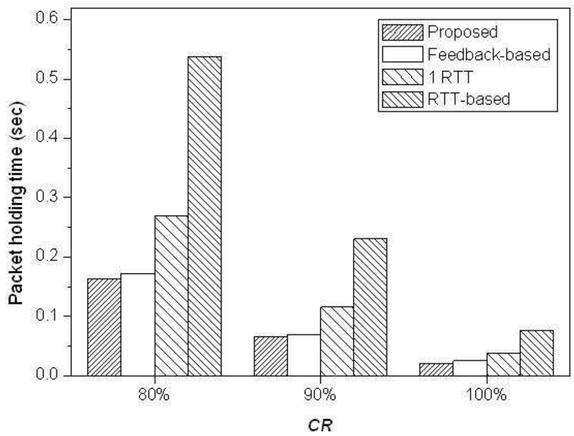


Figure 4.9: Packet holding times.

for a short period of time. Since a higher CR induces smaller hop counts between two caching nodes, the time required for retransmission requests is shorter and lost packets can be quickly be recovered. On the other hand, when a node receives data packets with a low CR, they are buffered for a long period of time. However, since the hop counts between two caching nodes are larger with a lower CR, the packet delivery rate drops and frequent transmission failures occur. In addition, the time required for a retransmission request is also longer, and thus, the packet holding time is longer for a lower CR.

Figure 4.10 shows that the average buffer requirements increase as the event generation rate increases. For the feedback-based method, the caching node that receives feedback messages can quickly remove packets from its buffer. In contrast, a caching node in the RTT-based method maintains data packets for a longer period of time. The proposed buffer management technique appropriately sets the packet holding time, which results in similar buffer requirements as the feedback-based method but without generating any additional messages. As shown in Figure 4.9, since the feedback-based method shows slight longer packet holding time than the proposed one, it can have larger buffer requirements than the proposed buffer management. This is remarkable especially on

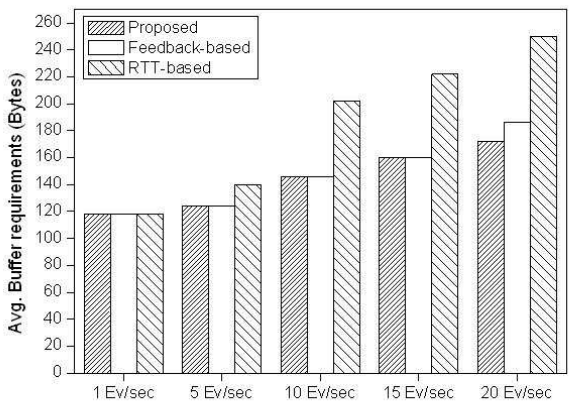


Figure 4.10: Average buffer requirements for the ten data flows: CRs for the flows are randomly selected from a range of 80% to 100%.

Table 4.1: Energy consumption for end-to-end transmissions.

CR	Proposed	Feedback-based	RTT-based
100 %	99.3 mJ	102.4 mJ	99.3 mJ
90 %	101.9 mJ	107.2 mJ	101.9 mJ
80 %	109.3 mJ	117.2 mJ	109.3 mJ

heavy load due to increased communication delay.

Table 4.1 shows the energy consumption for end-to-end transmissions. A simple energy consumption model based on LEACH [5] was employed for the simulations. The energy consumption model assumes free space wireless channel and $10m$ distance between two communicating nodes. The energy consumption is represented as $E = (0.11 \times 10^{-6}) \times m \times C_t$ $Joule$ for m-bit data and C_t total transmission count from a source node to a destination node. Although the feedback-based method has low buffer requirements, it has the highest energy consumption due to additional feedback messages. In contrast, the proposed method provide efficient buffer requirement as well as low energy consumption.

4.7 Summary

WSNs transmit data through multiple hops. End-to-end data transmission must recover lost data for reliable data transmissions. *Active caching* (AC) provides more flexible end-to-end delays and memory requirements for a given reliability than the existing recovery mechanisms (i.e., E2E, HBH). By using the proposed dynamic loss recovery with *Active caching*, a flexible end-to-end data transmission system can be designed.

The efficient loss recovery mechanism based on retransmission of lost packets is needed for reliable transmissions in WSNs. Retransmissions require sensor nodes to maintain data packets in their buffers. Since tiny sensor nodes have limited resources and demand very low-power consumption, an efficient buffer management is necessary for not only high utilization but also low-power. The proposed buffer management technique provides efficient buffer utilization by estimating transmission times of data packets. Moreover, there is no energy overhead required to issue additional messages to remove data packets from the buffers.

Chapter 5

Flexible Data Transmission in Wireless Body Area Networks

In this chapter, the thesis identifies the requirements of WBAN MAC protocols considering flexibility between medical and non-medical (CE) applications and proposes a novel WBAN MAC protocol which satisfies the requirements.

5.1 Overview

WBAN provides communication services in the vicinity of a human body. Since WBAN allows both medical and non-medical (CE) applications, WBAN MAC protocols should support the flexibility for the applications. Existing MAC protocols (i.e., TDMA and IEEE 802.15.4 MAC), however, have several restrictions. They provide only guaranteed communication services using time slots or the limited number of time slots (i.e., IEEE 802.15.4 MAC allows at most 7). Thus, they cannot support various WBAN services (e.g., medical or non-medical, contention or contention-free applications). In order to provide various WBAN services, the proposed MAC protocol expands the number of guaranteed time slots dynamically and exploits the Inactive period of a suferframe occasionally.

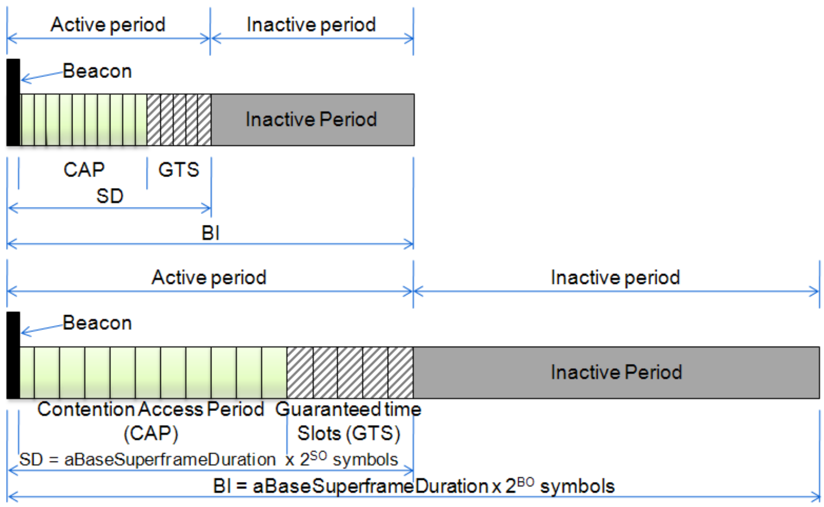


Figure 5.1: Superframe structure in IEEE 802.15.4.

5.2 Related work

WABN should support both medical and non-medical (CE) devices simultaneously. However, existing MAC protocols (i.e., TDMA or IEEE 802.15.4 MAC), which are being used in a body sensor network, do not satisfy the requirements in the specification of the IEEE 802.15.6 (we will deal with the requirements in Section 5.3).

TDMA was studied in early stage of WBAN researches, which considered only medical sensor devices [50]. When WBAN consists of various devices with different characteristics, TDMA may not be adequate.

IEEE 802.15.4 [23] uses a superframe structure in a beacon-enabled mode as shown in Figure 5.1. The superframe duration (SD) as an Active period is divided into 16 equal-sized time slots. A guaranteed time slot (GTS) is allocated in one or more slots to a device. If lots of GTS slots are allocated, a contention access period (CAP) is decreased. In addition, the GTS of IEEE 802.15.4 allows at most 7 devices. If IEEE 802.15.4 needs more CAP slots, a coordinator may increase a value of SO for the extension of CAP duration. By increasing SO, however, the size of a GTS slot also increases together.

Thus, it may lead to unnecessary increase of GTS slots.

To solve the above problems, there exist several studies to enhance GTS [51]. Assuming applications which transmit packets periodically, however, they focus on increasing the number of GTS slots and the bandwidth utilization. If the studies are applied to CE applications which generate sporadic packets in WBAN environments, large transmission latency results from an Inactive period. In addition, there are several proposals submitted to IEEE 802.15.6 TG [27], but they are not finalized yet.

Recently several studies about WBAN MAC have been introduced. For example, Ullah *et. al.* pointed out the problems of beacon-enabled IEEE 802.15.4 and proposed an asynchronous traffic-based wakeup mechanism [52]. Since a lot of works are based on IEEE 802.15.4 for on-body sensor network [53], we attempt to modify IEEE 802.15.4 for the purpose of WBAN.

5.3 Requirements of WBAN MAC protocols

Since WBAN serves various applications which are implemented by heterogeneous devices with different characteristics, it should provide flexibility among the devices or the applications. For the flexibility, WBAN MAC has following requirements [54, 55]:

- *Low-power consumption*: WBAN devices are implanted in a human body or are portable devices based on battery. Since the devices require ultra low-power, the efficiency of energy consumption is the major issue.

- *Duty cycle*: The requirement for duty cycle has a wide scope. In case of medical devices, duty cycle is important because it is related with low-power consumption. For low-power consumption, medical devices maintain sleep state for a long period of time and wake up when they need to communication. In contrast, non-medical (CE) devices do not rely on duty cycle relatively. They can have low, medium, or high duty cycle.

- *Latency*: WBAN requires various latency according to applications. In case of emergency traffic for medical applications, very short latency is required (for medical applications $\leq$ 125ms). Since the emergency traffic affects a human body directly, the latency should be guaranteed. Among CE applications, real-time services or guaranteed QoS services are also required short latency. However, CE devices requires slight longer latency than the medical applications (for CE applications $\leq$ 250ms).

- *Scalability*: WBAN can support 256 devices and WBAN MAC should considers extension of medical devices according to the Technical Requirement Document (TRD) [55]. In addition, for various applications, WBAN should provides flexible data transmission rate from low rate (i.e., 10Kbps) to high rate (i.e., 10Mbps).

- *Periodic and Non-periodic traffic*: Medical traffic generates periodically. The traffic generation period has a wide scope from 1ms to 1000sec. Thus, medical devices improve energy efficiency through duty cycle that is repeated between sleep and wake-up state. In contrast, CE devices generate event-driven traffic. That is, CE devices induce bursty traffic sporadically.

Although the energy efficiency is the most significant requirement, in WBAN, the flexibility of latency, QoS support, and scalability for various applications can be another challenging issue.

5.4 The proposed WBAN MAC protocol

Since providing the flexibility for various applications is the main goal, as mentioned earlier, we focus on the following ideas: First, the number of slots for applications using CFP should be sufficient, so that the number of tries to obtain a channel even when contention is present can be reduced. In IEEE 802.15.4 as shown in Figure 5.1, one or more GTS slots may be allocated to a device. Once GTS slots are allocated to a device, the device exclusively occupy the slots every superframe whether it sends data or not. Thus, if the device has a long period, bandwidth wastage is inevitable. In addition, since IEEE 802.15.4 permits only at most 7 devices for GTS, devices which are not allocated GTS have alternative but to use CAP. WBANs employ a star topology typically and thus a coordinator may manage lots of devices which require GTS. To support a large number of devices with GTS, we propose a **dynamic CFP allocation**. The proposed scheme dynamically allocates CFP slots in demand-driven manner, so that it can provide the flexibility while reducing bandwidth wastes. In addition, it allows more CFP allocations than IEEE 802.15.4.

Second, we exploit the **Opportunity period** in Inactive period for the flexible ranges of the latency. In IEEE 802.15.4, the Inactive period is determined by BO and SO in a beacon and all the devices sleep in the period. If CAP is insufficient due to increased temporary traffics, IEEE 802.15.4 expands CAP by increasing SO in a beacon. However, when SO increases, the size of a CFP slot also exponentially increases. To support sporadic traffics of CE applications flexibly, the Opportunity period is proposed.

Figure 5.2 depicts the proposed superframe structure. As compared with the superframe of IEEE 802.15.4 in Figure 5.1, the CFP allocation period is added and the duration of CFP is variable due to our dynamic CFP allocation. Since the Active period (CAP + CFP) is fixed in each superframe, the duration of CAP is also variable but the minimum region of CAP is guaranteed through our Maginot line mechanism. The Inactive period of IEEE 802.15.4 can be switched into the Opportunity period in our protocol. The following subsections will give the detailed description.

5.4.1 Dynamic CFP allocation

For dynamic CFP allocation, we should provide a mechanism for devices to request CFP slots to the coordinator. This request can be also contention-free or contention-access

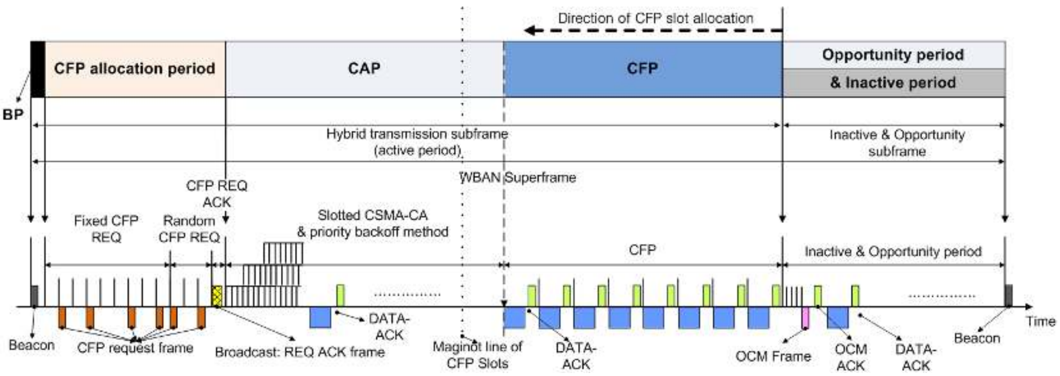


Figure 5.2: Proposed superframe structure

similar to data transmission. Therefore our CFP allocation period consists of two types of subperiod. In the Fixed CFP REQ, there exist small request slots, so called mini-slots, mapped to each device (i.e., one-to-one mapping between mini-slot and device). Since the number of mini-slots is limited, however, a device which is not allocated the mini-slot selects a mini-slot randomly in Random CFP REQ subperiod and send its request. If a collision occurs in the mini-slot, the devices retry in the next superframe. In addition, CFP slots can be allocated without requests through the beacon (BP) like IEEE 802.15.4.

In summary, there exist three types of CFP allocation: in BP, Fixed CFP REQ, and Random CFP REQ. The allocation in BP has no overhead because there is no request message. The overhead in Random CFP REQ is the largest because of collision possibility. The policy of CFP-slot allocation method can be expressed like: As a device sends data more frequently, the device should be provided a CFP-slot allocation method which has smaller overhead.

In our dynamic CFP allocation, devices which request CFP slots are distinguished into 3 groups as follows:

- *Group 1* : Devices such that $T_p = 1$.
- *Group 2* : Devices such that $1 < T_p < \eta$.

- *Group 3* : Devices such that $T_p \geq \eta$.

T_p is the transmission period of the device and the unit is a superframe. For example, if $T_p = 5$, the device sends data every 5 superframes. When a device registers to the coordinator, T_p is delivered together. Since devices in *Group 1* transmit data every superframe, CFP slots for *Group 1* devices are allocated in BP. Devices in *Group 2* and *Group 3* are allocated CFP slots dynamically in CFP allocation period. Similar to IEEE 802.15.4, the maximum number of devices in *Group 1* is 7 and thus the 8^{th} device in *Group 1* belongs to *Group 2*. Since the number of mini-slots in Fixed CFP REQ subperiod is limited, the number of devices in *Group 2* is controlled with the parameter η. In other words, the coordinator reduces the value of η when the number of devices in *Group 2* exceed its upper limit.

After the coordinator collects CFP request frames during Fixed CFP REQ and Random CFP REQ subperiods, it analyzes the requests and broadcasts the result (REQ ACK) to allocate CFP slots for *Group 2* or *Group 3* devices in CFP REQ ACK period. While allocating CFP slots, the coordinator allocates them to reverse direction from the end point of Active period. Since the Active period consists of CAP and CFP, however, it is necessary to guarantee the minimum region of CAP similar to IEEE 802.15.4. Our allocation of CFP slots to reverse direction from the end point of Active period are available until **Maginot line** as depicted in Figure 5.2.

The dynamic CFP allocation period in the proposed protocol is required to deliver overhead messages such as CFP request and REQ ACK frames. However, there are a lot of wastes of GTS slots statically allocated in IEEE 802.15.4 if the transmission period is larger than a superframe (i.e., the slots are reserved but not used.). In spite of the overhead, it is proved in Section 5.5 that the throughput of the proposed protocol outperforms that of IEEE 802.15.4 in WBAN environments which have various medical and CE devices.

5.4.2 Opportunity period

In WBAN environments as mentioned earlier, CE devices may generate sporadic and burst data. In order to support large amount of sporadic data and to reduce the transmission latency, we propose the Opportunity period in Inactive period. A coordinator waits control frames (Opportunity Contention Message, OCM) from devices at the initial stage of Inactive period. If the coordinator receives OCMs, it notifies devices to switch the Inactive period into the Opportunity period by broadcasting OCM ACK. In short, instead of changing BO and SO values which configure each period of superframe as in IEEE 802.15.4, the proposed WBAN MAC protocol provides flexible transmissions through the temporary switching method between the Inactive period and the Opportunity period. Since CE devices mainly use the Opportunity period, medical devices can sleep at the initial stage of Inactive period immediately.

When we exploit the Opportunity period, it has a few overheads. A coordinator and devices cannot immediately sleep in the Inactive period because of OCM and OCM ACK. In addition, there exist additional energy consumption to transmit OCM and OCM ACK messages. However, the overheads are inevitable to provide flexible transmissions in WBAN and can be neglected in case of the coordinator and CE devices which have relatively large capacity of battery power compared with medical devices.

5.5 Performance evaluation

We first describe our simulation model to compare the performance of the proposed WBAN MAC protocol with that of IEEE 802.15.4. As for the PHY model, we assume ISM band, O-QPSK modulation, 2,000kcps chip rate, and 250kbps data rate [23]. In addition, both the proposed and IEEE 802.15.4 MAC protocols use the superframe structure, and BO and SO determine the superframe length and the active period, respectively. In order to satisfy the latency requirement in Section 5.3, we set BO=4 (245.76ms of superframe)

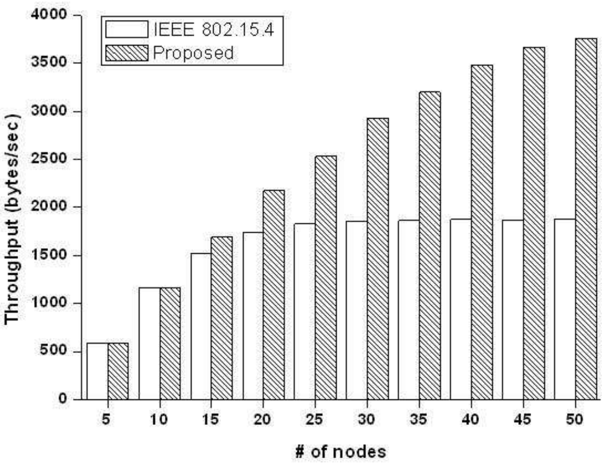


Figure 5.3: Throughput comparison (medical devices).

and SO=3 (122.88ms of active period).

Next, the traffic model is as follows: There exist 5 to 50 medical devices of which the period is 100ms (20%), 400ms (20%), 800ms (20%), 1s (20%), and 10s (20%). The initial value of η is set 10. They send a packet of 40 bytes every period. One CE device sends a message of 5000 bytes sporadically. The message is split into MAC-layer packets of 127 bytes which is the maximum size of IEEE 802.15.4 [23]. The above simulation model has been implemented in our simulator using C++.

Figures 5.3 and 5.4 show the throughput and the latency, respectively, when there exist only medical devices. The IEEE 802.15.4 MAC protocol allocates CFP slots to at most 7 devices statically and thus devices which are not allocated CFP slots should compete to use CAP. Furthermore, there exist bandwidth wastes when devices which are allocated CFP slots do not transmit data. As shown in Figure 5.3, the throughput of IEEE 802.15.4 does not increase when there are more than 25 medical devices. Since the proposed protocol allocates CFP slots dynamically to devices which transmit data in the superframe, however, the throughput of our protocol increases even when there

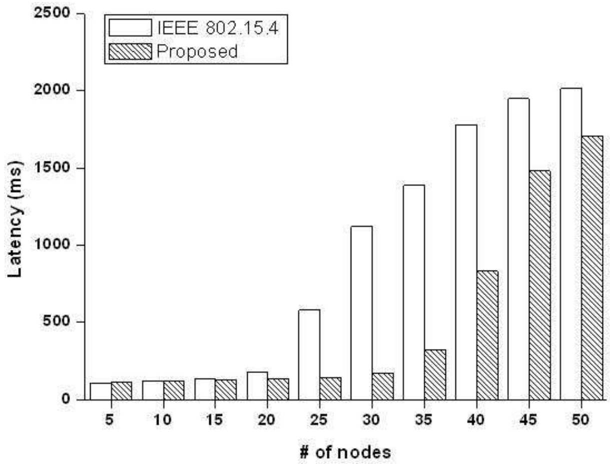


Figure 5.4: Latency comparison (medical devices).

are more than 25 medical devices. As we can expect, both protocols exhibit the similar performance in terms of the throughput when there are less than 10 medical devices.

In terms of the latency, the proposed protocol also outperforms IEEE 802.15.4 as shown in Figure 5.4. If devices which are not allocated CFP slots do not acquire CAP slots, in IEEE 802.15.4, they should retry in the next superframe. In our protocol, however, relatively large numbers of devices can be allocated CFP slots and thus the average transmission latency of the proposed protocol is smaller than that of IEEE 802.15.4 as depicted in Figure 5.4. As the number of medical devices is larger, we can find from Figures 5.3 and 5.4 that the proposed protocol is superior to IEEE 802.15.4 through the dynamic CFP allocation.

Figure 5.5 shows the latency when a CE device is added. In IEEE 802.15.4, the CE device should contend medical devices which are not allocated CFP slots. However, it can use the Opportunity period in our protocol, so that the latency can be reduced dramatically. We can conclude that the proposed protocol can be used flexibly in a variety of WBAN applications while providing high throughput and low latency.

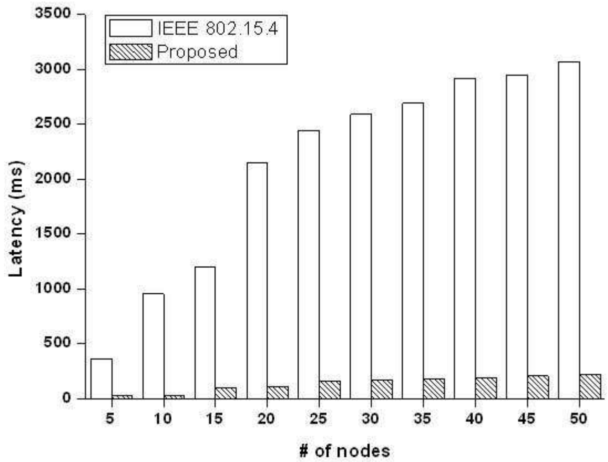


Figure 5.5: Latency comparison (CE device).

5.6 Summary

In this chapter, the thesis has identified the requirements of WBAN MAC protocols and proposed a WBAN MAC protocol which satisfies the requirements. Since the proposed WBAN MAC protocol employs the dynamic CFP allocation and opportunity period, it can be used flexibly in various WBAN devices and applications which require from small to large duty cycle, latency, and scalability. In addition, the flexibility has been validated through extensive simulations.

Chapter 6

Conclusions and Future work

In this chapter, we conclude from the research results presented in this thesis and suggest few directions for future work.

6.1 Conclusions

This thesis has proposed data transmission schemes for wireless personal area networks (WPANs). Among WPAN technologies, transmission schemes for wireless sensor network (WSN) for low-rate WPAN (LR-WPAN) and wireless body area network (WBAN) are proposed. This thesis consisted of three parts divided by *Practical Data Transmission in Cluster-based Sensor Networks, Reliable data transmission in WSNs, and a novel WBAN MAC protocol* sections.

The first part has analyzed the optimal ratio of clusters for hierarchical wireless sensor networks (cluster-based sensor network) and proposed d-hop clustering using the optimal ratio. In addition, the thesis has described multi-hop transmission in an intra/inter cluster. In the cluster-based sensor network, a clustering method mainly affects on the network performance and the ratio of clusters is the major factor to determine energy consumption of the network. The proposal of the first part has derived the optimal ratio of cluster using the Poisson point process on Voronoi tessellation. When the optimal ratio of clusters is determined, the network should keep the ratio for energy efficiency. The proposed clustering method, which expands clusters, provides the way to maintain the ratio of clusters. Moreover, multi-hop transmission is also considered for tiny sensor nodes in a POS environment.

The second part has proposed the flexible loss recovery mechanism and the buffer management technique for the loss recovery. In general, wireless channel has more errors than wired channel and the channel error accumulates exponentially over multi-hops. Thus, for reliable data transmission, loss recovery mechanism for lost packets is needed. The proposal of the second part has provided the flexibility for the desired communication reliability (CR) of applications. In addition, The proposal has also provided the efficient buffer management technique. In tiny sensor nodes, the efficient buffer management lead to safely removing packets from buffers as well as it makes data packets occupy buffers during proper times.

The third part has proposed a dynamic CFP allocation and opportunity contention-based WBAN MAC protocol. As mentioned earlier, WBAN is the next generation of wireless technology for WPAN. However, the existing WBAN MAC protocols do not reflect the WBAN features, which allow the flexibility between medical and non-medical (consumer electronics: CE) applications. The proposal of the third part provides the flexible WBAN MAC protocol, which satisfies the requirements of WBAN MAC.

6.2 Future work

Research issues and solutions described in this thesis have shown various challenges for data transmission of WPAN. In WSN part, we have mainly addressed the clustering method. Although we have employed simple multi-hop transmission method, the proposed clustering scheme can be applied to improved multi-hop transmission method. In addition, we have dealt with the reliable transmission over WSN but the reliable transmission method can function over other wireless networks such as Ad-hoc network or Mesh network.

Our proposed WBAN MAC protocol identifies the requirements and provides solutions for the requirements. These days, more requirements are required for various WBAN services. Thus, the proposed WBAN MAC reflects more requirements. Moreover, upper layer protocols considering the proposed WBAN MAC are need for efficient WBAN services.

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Appendix A
Calculation of the ratio of cluster-heads

From the aggregate characteristics (S_f), the hop-count of all member nodes in a Voronoi cell can be calculated as

$$E[H_c|N = n] = \lambda_0 \int_0^\infty \left\lceil \frac{l}{r} \right\rceil 2\pi l e^{-\lambda_1 \pi l^2} dl, \tag{A.1}$$

where the distance between relay nodes is r and the length of each node is l. To calculate Eq. (A.1), a specific formula of definite integrals in *Differential Calculus* is used [56]

$$\int_0^\infty e^{-ax} dx = \frac{1}{a}, \qquad a > 0. \tag{A.2}$$

The optimal ratio of cluster-heads p is derived by the total energy consumption cost $E[C]$ from Eq. (3.12). p can be obtained by differential of the $E[C]$. Then, p is a solution of

$$cp^{3/2} - p - 1 = 0, \tag{A.3}$$

where c is $2\sqrt{\lambda A}$. λ is the intensity of deployed sensor nodes and A is area in which sensor nodes are deployed. Eq. (A.3) has one real root and two imaginary roots. The second derivative of Eq. (A.3) is positive for the real root and the real root is the optimal ratio to minimize the energy consumption cost

$$p = \left[\frac{1}{3c} + \frac{2^{1/3}}{3c(2 + 27c^2 + 3\sqrt{3}c\sqrt{27c^2 + 4})^{1/3}} + \frac{(2 + 27c^2 + 3\sqrt{3}c\sqrt{27c^2 + 4})^{1/3}}{3c} \cdot \frac{1}{2^{1/3}} \right]^2. \tag{A.4}$$

Appendix B

Packet loss model

In chapter 4, simple packet loss model is used. This appendix provides more accurate packet loss model for the wireless channel. The packet loss rate p_i consists of a uniform link error (p_l) and a contention error (p_c). p_c occurs when nodes try to transmit data simultaneously. It can be calculated by using a probability of activity (p_a) of nodes in a transmission range. p_a is the probability of nodes in an active state for communication and is less than 0.1 for many IEEE 802.15.4 applications [57]. Howitt and Gutierrez [57] analyzed p_c using p_a. Since data flows concentrate on a sink node, it is necessary to consider that the value of p_a increases when a node is close to a sink node.

If we assume p_a has an exponential distribution with mean λ according to a distance from a sink node, its density function is represented as

$$f(x) = \lambda e^{-\lambda x}, \qquad x \geq 0, \tag{B.1}$$

where λ is the maximum value of p_a. And its distribution function is represented as

$$F(x) = \int_0^x \lambda e^{-\lambda x} dx = 1 - e^{-\lambda x}. \tag{B.2}$$

Then, p_a between two distances from a sink node, α and β, is represented as

$$p_a(\alpha \leq x \leq \beta) = e^{-\lambda \alpha} - e^{-\lambda \beta}. \tag{B.3}$$

Since WSNs are based on multi-hop transmission and the p_a shows a different value in each hop, we can estimate p_a in each hop by applying a hop-count to a distance of the distribution function. When p_a is determined, p_c of a node can be calculated using the number of neighbor nodes (N_t). In a transmission rage, a probability of activity for each node is $p_a/(N_t + 1)$. Thus, p_c is represented as

$$p_c = 1 - \left(1 - \frac{p_a}{N_t + 1}\right)^{N_t}. \tag{B.4}$$

Then, p_i is

$$p_i = p_l + p_c. \tag{B.5}$$

Although we employ this pass loss model for our proposals, we obtain the same results with the simple packet loss model in chapter 4.