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Proposal of a hierarchical topology and spatial reuse superframe for enhancing throughput of a cluster-based WBAN

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A cluster topology was proposed with the assumption of zero noise to improve the performance of wireless body area networks (WBANs). However, in WBANs, the transmission power should be reduced as low as possible to avoid the effect of electromagnetic waves on the human body and to extend the lifetime of a battery. Therefore, in this work, we consider a bit error rate for a cluster-based WBAN and analyze the performance of the system while the transmission of sensors and cluster headers (CHs) is controlled. Moreover, a hierarchical topology is proposed for the cluster-based WBAN to further improve the throughput of the system; this proposed system is called as the hierarchical cluster WBAN. The hierarchical cluster WBAN is combined with a transmission control scheme, that is, complete control, spatial reuse superframe, to increase the throughput. The proposed system is analyzed and evaluated based on several factors of the system model, such as signal-to-noise ratio, number of clusters, and number of sensors. The calculation result indicates that the proposed hierarchical cluster WBAN outperforms the cluster-based WBAN in all analyzed scenarios.

KEYWORDS
cluster topology, hierarchical cluster WBAN, spatial reuse superframe, transmission control schemes, wireless body area networks

1 | INTRODUCTION

1.1 | Scope and motivation

Owing to the increasing number of senior citizens (persons who are 65 years old and above) all over the world, many countries have a large number of elderly population. To survey the health situation of elderly people, remote monitoring of the status of the body and the surrounding environment is becoming more important. One of the monitoring systems is a wireless body area network (WBAN), which consists of interconnected sensors and a coordinator. These sensors are distributed around the body, to continuously monitor data and send it to the coordinator; the coordinator gathers the data and forwards it to a health care center through existing networks.

Owing to the increasing use of WBANs, in February 2012, the IEEE 802.15.6 standard was established for WBANs [1]. Based on IEEE 802.15.6, the topology of a WBAN is defined as star plus one; thus, the topology of a WBAN system can be divided into two types: type 1: star-topology, where all sensors transmit the signal directly to the coordinator; and type 2: dual-hop topology, where the sensor transmits the signal to the coordinator via other sensors. In a type 1 topology, a sensor should use high power to transmit the signal because the coordinator is not always close to the sensor. Therefore, the lifetime of the sensors is shortened; moreover, each sensor causes an interference to almost all other sensors. Furthermore, the connection between sensors and the coordinator may fail owing to the interruption caused by the body, especially when the human is moving. Conversely, in a type 2 topology, as each sensor transmits the signal to its neighboring sensor, the transmission power, transit area, and effective area are small. Therefore, the number of sensors that interfere with the transmission of a sensor decreases and the lifetime of sensors increases. Additionally, even if the direct connection between a sensor and the coordinator fails, the sensor can transmit its signal to the coordinator via another sensor that is connected to the coordinator.

A category under type 2 topology is a cluster topology in which a sensor is assigned into one cluster, which sends signals to the coordinator through its own cluster header (CH). The cluster topology has been researched in several fields, such as ad hoc networks, mobile networks, intelligent transportation systems, and also WBANs. This topology can extend the lifetime and/or reduce the energy consumption of sensors; however, the transmission of a data packet affects all sensors and the CH in a particular cluster twice (the details are explained in the following section); consequently, it restricts the performance of the cluster topology-based WBAN systems. We proposed a hierarchical topology for cluster-based WBANs to solve this problem and to improve the performance of the cluster topology. The contributions of our work are as follows:

- A spatial reuse superframe scheme for a cluster-based WBAN was proposed in our previous work; however, a noise-free environment was assumed. We propose a method to analyze the spatial reuse superframe scheme in the case of the existence of bit error rate (BER).
- We propose a hierarchical topology for the cluster-based WBAN; further, equations were derived for analyzing the performance of the hierarchical topology.
- The combination of the hierarchical cluster topology and other control schemes, such as complete control and spatial reuse superframe, is considered to further improve the throughput of the system.
- The effect of other factors, that is, signal-to-noise ratio (SNR), number of sensors, number of clusters, number of spatial reuse superframes, on the throughput is discussed to evaluate the proposed scheme.

1.2 | Methods

Based on a statistical method, the proposed system model is represented by mathematical equations, and the performance of this system was analyzed by solving these equations.

MATLAB was also used to calculate the probabilities as well as the channel capacity in several scenarios of the channel model. The channel capacities in these scenarios were plotted and compared to evaluate the proposed combination of the hierarchical cluster topology with control methods.

1.3 | Related research

There are many studies on type 1 topology called as one-hop star topology. Rashwand et al. demonstrated that the length of a superframe sufficiently affects the throughput of a system [2]. Moreover, the performance of WBANs was analyzed in non-saturation [3] and saturation conditions [4] using carrier-sense multiple access with collision avoidance (CSMA/CA) protocol. The maximum throughput and the related delay of WBANs were discussed for several frequencies considering the conditions of zero collision and BER [5]. Furthermore, Khan et al. provided equations to calculate the throughput, energy consumption, and delay while using CSMA/CA for every user priority (UP) with the existence of path loss [6]. In [7], the authors researched the effect of UP on the average values of throughput and delay and determined that the system can obtain high throughput and low delay for low packet generation rates, which is appropriate for application in WBANs. The discrete-time Markov chain [8] and a statistical method [9] were proposed to analyze the reliability and throughput of WBANs with CSMA/CA protocol. These researchers indicated that the proposed methods can be applied in both saturation and non-saturation conditions. Moreover, a death probability and game theoretic framework were also proposed to analyze the energy efficiency [10] and inter-user interference cancelation [11].

In the type 2 topology, a multiple-hop topology for WBANs was proposed and analyzed [12]; furthermore, the performance of a multiple-hop system was discussed based on energy consumption and throughput. The research determined that the multiple-hop system outperforms the one-hop star system. Furthermore, a cluster topology for WBANs was proposed and the number of clusters was optimized to obtain the highest throughput [13]. Conversely, the authors in [14] proposed a control on the medium access control (MAC) layer and the spatial reuse superframe scheme to improve the throughput of the system. However, in these papers, the noise-free condition was assumed, and the performance was analyzed in an ideal condition. In WBANs, the transmission power should be reduced to avoid the effect of electromagnetic waves on the human body and to extend the lifetime of the sensors. Consequently, the assumption of noise-free condition is no longer applicable and the WBAN system should be discussed considering noisy channels.

1.4 | Structure of the paper

The rest of the paper is organized as follows. Section 2 briefly describes the previous work of the spatial reuse superframe scheme, and then, proposes a method to analyze this scheme considering the existence of BER. The hierarchical cluster topology and its combination with the spatial reuse superframe scheme are proposed in Section 3. Section 4 shows the calculation results of the proposed method and compares it with existing methods. The statistical results and discussion are presented in Section 5.

2 | CONTROL SCHEMES WITH BIT ERROR RATE (BER)

2.1 | System model of cluster-based wireless body area network (WBAN)

The cluster-based WBAN is represented in Figure 1. Sensors are assumed to be uniformly distributed on the whole body and equally divided into many clusters. A cluster consists of a CH and several sensors. The CHs control the transmissions of its own member sensors according to the information of the coordinator and forward the received data to the coordinator. The CHs do not generate vital information by themselves, whereas the sensors sense the information regarding the human body and send vital data packets to the CH during their own transmission allocation time slots. The transmission of signals from the sensors to their CH and from the CH to the coordinator is assumed to be operated by the CSMA/CA scheme.

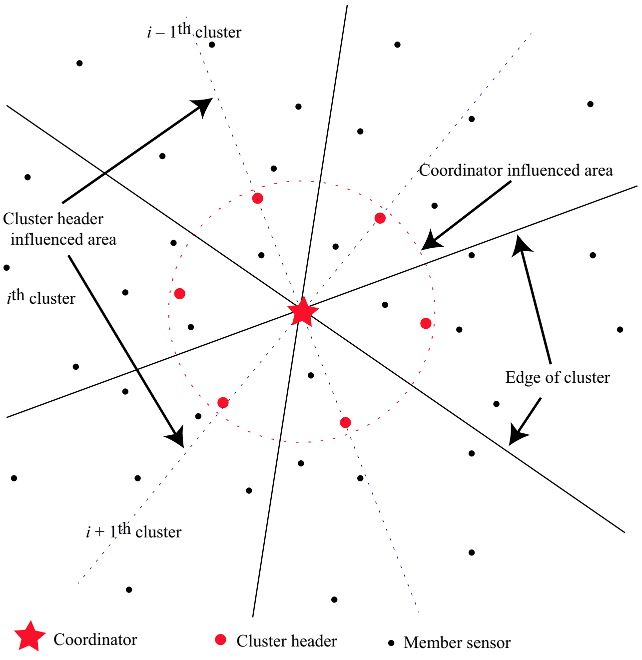

FIGURE 1 Cluster model for wireless body area network (WBAN)

The UP and access probability of every sensor, (τ), and the number of sensors in each cluster, (N_s), are assumed to be the same. Let N denote the total number of sensors (excluding CHs); then, the number of clusters is $N_c = N/N_s$. The number of sensors in the coordinator influenced area is denoted by N_h.

2.2 | Definition of control schemes

2.2.1 | No-control scheme

When all the sensors and CHs transmit a data packet without any specific control by just following the CSMA/CA scheme, it is called as a no-control scheme. In a no-control scheme, the CHs are affected by not only the sensors in their cluster, but also the CHs and sensors of nearby clusters. Figure 1 describes six clusters, which are separated from the edges of the clusters.

Two CHs and half of the sensors in the nearby clusters ($i-1$th and $i+1$th clusters) that are located within the CH influenced area can affect the performance of the CH of the ith cluster. Conversely, the coordinator is affected by all CHs and sensors that are located within the coordinator influenced area.

2.2.2 | Complete control scheme

In a no-control scheme, all the sensors can transmit data packets at any time when they have a packet to send. Initially, the packet is transmitted to the CH and then forwarded to the coordinator. Therefore, transmission of a packet affects not only the sensors in the same cluster but also the sensors in the nearby clusters. The coordinator is also affected by N_h sensors and all CHs. These problems result in a low throughput for the system.

To improve the throughput of the system, transmission of every cluster is completely controlled, meaning each cluster is allowed to transmit in a different time slot, called a superframe. Therefore, the transmission of a packet only affects the sensors in the same cluster, and the coordinator is affected by N_h/N_c sensors and one CH at a time. Therefore, the transmission success probability is expected to be high.

2.2.3 | Spatial reuse superframe scheme

In the complete control scheme, every cluster is allowed to transmit in its own superframe; thus, the transmission allocation time for every cluster is low. As a result, the performance cannot be considerably improved.

For more improvement of the performance, the spatial reuse superframe scheme was proposed by [14], where several clusters were allowed to transmit in the same superframe; however, neighbors should transmit in different superframes. The number of spatial reuse superframes, k, is defined as the ratio of the number of total clusters (N_c) to the number of clusters that are allowed to transmit in the same superframe. Thus, at a time, the coordinator is affected by N_h/k sensors and N_c/k CHs. The transmission success probability of the spatial reuse superframe scheme is lower than that of the complete control scheme; however, the transmission allocation time for every cluster is higher; hence, the performance is expected to improve.

2.3 | Performance analysis method for a system with BER

The spatial reuse superframe scheme was proposed in an earlier study; however, it was analyzed with the assumption of noise-free conditions. As explained in Section 1, the BER should be taken into consideration; consequently, a new method to analyze the performance of the system with BER is described in this section.

2.3.1 | No-control scheme

In this scheme, the transmissions of all sensors and CHs are not controlled by the coordinator and it just follows the CSMA/CA algorithm. Let $P^\mathrm{s}_\mathrm{suc}$ denote the transmission success probability of all sensors in a cluster; then, the access probability of the CH is calculated by

$$\tau_\mathrm{c} = P^\mathrm{s}_\mathrm{suc}\tau. \tag{1}$$

The transmission of packets from a sensor to the CH is successful if the sensor successfully accesses the channel and the CH successfully decodes the received packet. Furthermore, the sensor successfully accesses the channel if the other sensors and CHs in the CH influenced area maintain silence or are receiving the data. Thus, $P^\mathrm{s}_\mathrm{suc}$ is represented as follows:

$$P^\mathrm{s}_\mathrm{suc} = N_\mathrm{s}\tau(1-\tau)^{N_\mathrm{s}-1}(1-\tau_\mathrm{c})^3(1-\tau)^{2\frac{N_\mathrm{s}}{2}}(1-\mathrm{PER}), \tag{2}$$

where PER is the packet error rate, which is described as

$$\mathrm{PER} = 1-(1-\mathrm{BER})^{\frac{E[P]}{N_\mathrm{code}}}, \tag{3}$$

where N_code is a block length of a code word and $E[P]$ is a payload of the packet. According to the IEEE 802.15.6 standard, a Bose-Chaudhuri-Hocquenghem (BCH) code, BCH(63,51), is adopted; thus, the block length, $N_\mathrm{code} = 63$, the number of information bits in every block, $K_\mathrm{code} = 51$, and the error correction capability, $T_\mathrm{code} = 2$. The BER of the BCH code is represented in the work of [15] as follows:

$$\mathrm{BER} = \sum_{j=T_\mathrm{code}+1}^{N_\mathrm{code}} \binom{N_\mathrm{code}}{j} p^j_\mathrm{mod}(1-p_\mathrm{mod})^{N_\mathrm{code}-j}, \tag{4}$$

where p_mod is the BER after demodulation. Reference [16] indicated that because the modulation of this bandwidth is $\pi/2$-DBPSK, $P_\mathrm{mod} = (1/2)\,\mathrm{e}^{-\mathrm{SNR}}$.

Conversely, a CH can transmit successfully if the other CHs and N_h sensors in the coordinator influenced area maintain the silence; furthermore, the coordinator should successfully decode the received packet. The transmission success probability and the idle probability of CHs are respectively represented by

$$\begin{aligned} P^\mathrm{c}_\mathrm{suc} &= N_\mathrm{c}\tau_\mathrm{c}(1-\tau_\mathrm{c})^{N_\mathrm{c}-1}(1-\tau)^{N_\mathrm{h}}(1-\mathrm{PER}), \\ P^c_\mathrm{idle} &= (1-\tau_\mathrm{c})^{N_\mathrm{c}}(1-\tau)^{2N_\mathrm{s}}. \end{aligned} \tag{5}$$

The idle probability is the probability that a channel is free, meaning that no sensor is transmitting. Let $P^\mathrm{c}_\mathrm{fail} = 1 - P^\mathrm{c}_\mathrm{suc} - P^\mathrm{c}_\mathrm{idle}$ denote the failed probability, which implies that the transmission of a CH has failed owing to collision or unsuccessful decoding. Consequently, the throughput of the system is expressed as:

$$C = \frac{P^\mathrm{c}_\mathrm{suc}R_\mathrm{code}E[P]}{P^\mathrm{c}_\mathrm{idle}T_\mathrm{s} + P^\mathrm{c}_\mathrm{suc}T + P^\mathrm{c}_\mathrm{fail}T_\mathrm{c}}, \tag{6}$$

where $K_\mathrm{code}/N_\mathrm{code}$ is the code rate. T_s, T, and T_c are defined by [9] as the time of a CSMA slot, successful transmission time, and time taken for collided transmission of packets, respectively.

2.3.2 | Complete control scheme

In this scheme, the coordinator permits every cluster to transmit in different superframes, which are distinguished by a beacon signal. In fairness to all clusters, the length of the superframes is assumed to be equal. At any time, only one cluster is allowed to be active; the CH and the sensors in this cluster transmit and receive data packets, whereas the CHs and the sensors in the other clusters go to sleep to save energy. Therefore, the transmission success probability of the sensors and CH and the idle probability are similar to that of one-hop star topology. However, in this work, the BER is taken into consideration; consequently, these probabilities are represented as follows:

$$\begin{aligned} P^\mathrm{s}_\mathrm{suc} &= N_\mathrm{s}\tau(1-\tau)^{N_\mathrm{s}-1}(1-\tau_\mathrm{c})(1-\mathrm{PER}), \\ P^\mathrm{c}_\mathrm{suc} &= N_\mathrm{c}\tau_\mathrm{c}(1-\tau_\mathrm{c})^{N_\mathrm{c}-1}(1-\tau)^{\frac{N_\mathrm{h}}{N_\mathrm{c}}}(1-\mathrm{PER}), \\ P^\mathrm{c}_\mathrm{idle} &= (1-\tau_\mathrm{c})(1-\tau)^{N_\mathrm{s}}. \end{aligned} \tag{7}$$

As the sensor in the complete control scheme transmits in one of the N_c superframes, the access probability of a CH in this scheme is described by

$$\tau_\mathrm{c} = P^\mathrm{s}_\mathrm{suc}N_\mathrm{c}\tau. \tag{8}$$

When compared to the no-control scheme (2), the transmission success probability of sensors in the complete control scheme (7) is higher; furthermore, a similar probability is demonstrated for the transmission success probability of

CHs. However, the transmission allocation time for every cluster in the complete control scheme is smaller by N_c times than that in the no-control scheme. Therefore, the throughput of the complete control scheme should be divided by N_c.

$$C=\frac{1}{N_\mathrm{c}}\frac{P^\mathrm{c}_\mathrm{suc}R_\mathrm{code}E[P]}{P^\mathrm{c}_\mathrm{idle}T_\mathrm{s}+P^\mathrm{c}_\mathrm{suc}T+P^\mathrm{c}_\mathrm{fail}T_\mathrm{c}}. \tag{9}$$

2.3.3 | Spatial reuse superframe scheme

The complete control scheme can reduce the effect of transmission of a packet on sensors and CHs; consequently, the transmission success probability increases. However, the transmission allocation time decreases; thus, the throughput is expected to not increase considerably. The spatial reuse superframe scheme was proposed for a noise-free system by [14] to increase the throughput of the system. In this work, we considered the spatial reuse superframe scheme for a system with BER. The spatial reuse super-frame scheme is explained in Section 2.2.3; consequently, the transmission success probability of sensors and CHs and the idle probability are respectively described by

$$\begin{aligned}P^\mathrm{s}_\mathrm{suc}&=N_\mathrm{s}\tau(1-\tau)^{N_\mathrm{s}-1}(1-\tau_\mathrm{c})(1-\mathrm{PER}),\\P^\mathrm{c}_\mathrm{suc}&=N_\mathrm{c}\tau_\mathrm{c}(1-\tau_\mathrm{c})^{\frac{N_\mathrm{c}}{k}-1}(1-\tau)^{\frac{N_\mathrm{h}}{k}}(1-\mathrm{PER}),\\P^\mathrm{c}_\mathrm{idle}&=(1-\tau_\mathrm{c})^{\frac{N_\mathrm{c}}{k}}(1-\tau)^{N_\mathrm{s}}.\end{aligned} \tag{10}$$

Being similar to the complete control scheme, the access probability of the CHs and the throughput of the spatial reuse superframe scheme are calculated by

$$\tau_\mathrm{c}=P^\mathrm{s}_\mathrm{suc}k\tau, \tag{11}$$

$$C=\frac{1}{k}\frac{P^\mathrm{c}_\mathrm{suc}R_\mathrm{code}E[P]}{P^\mathrm{c}_\mathrm{idle}T_\mathrm{s}+P^\mathrm{c}_\mathrm{suc}T+P^\mathrm{c}_\mathrm{fail}T_\mathrm{c}}. \tag{12}$$

By comparing the spatial reuse superframe schemes for the no-control and complete control schemes, it was determined that the no-control scheme is similar to the spatial reuse superframe with $k=1$, and the complete control scheme is similar to the spatial reuse superframe with $k=N_\mathrm{c}$.

3 | HIERARCHICAL TOPOLOGY FOR CLUSTER-BASED WBAN

In the previous section, a cluster-based WBAN with BER was analyzed using several control schemes. The sensors and CH of a cluster transmit packets in the same superframe; the packets are transmitted from the sensors to the CH and then forwarded to the coordinator. Therefore, the transmission of a packet affects other sensors twice, and it deteriorates the performance of the cluster-based system. The hierarchical topology for a cluster-based WBAN, which is called as the hierarchical cluster WBAN, was proposed to solve this problem.

3.1 | System model of hierarchical cluster WBAN

Figure 2 shows the system model of a hierarchical cluster WBAN. Initially, similar to the cluster-based system, all sensors are divided equally among several clusters and every cluster has a CH. In the previous system, the sensors and CH of a cluster transmitted packets in the same superframe; however, the hierarchical topology was proposed to avoid the twofold effect caused by the transmission of a single packet. In the hierarchical topology, the transmissions of sensors and CHs are separated to different time slots; sensors transmit to CHs in the first time slot, whereas CHs forward the received packets to the coordinator in the second time slot, when the sensors are sleeping. The lengths of the first and second time slots are assumed to be the same, and the transmission protocol of all sensors and CHs is the CSMA/CA protocol based on IEEE 802.15.6.

3.2 | Combination of hierarchical cluster and control scheme

The control of transmission for cluster-based systems, which was explained in the previous section, can be applied to the hierarchical cluster. The number of CHs is much fewer than the number of sensors; thus, all CHs transmit during the second time slot. The control of transmission is applied to the first time slot, which implies the transmission of the sensors.

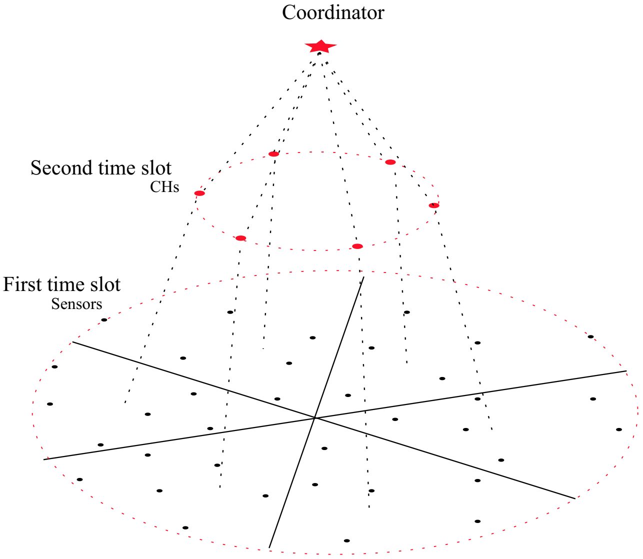

FIGURE 2 Hierarchical topology for cluster-based WBAN

3.2.1 | In the first time slot

For the no-control scheme, sensors in all clusters can transmit at any time; however, in the hierarchical cluster scheme, the sensors transmit in the first time slot. Therefore, in a combination of hierarchical cluster and no-control schemes, all sensors can transmit at any time in the first time slot. As discussed in Section 2.3, the transmission success probability of sensors is represented as follows. Note that CHs in the hierarchical cluster scheme forward the received packets in the second time slot and the calculation of BER in both the hierarchical cluster and the cluster-based systems are the same as that described in Section 2.3.

$$P^{\mathrm{s}}_{\mathrm{suc}} = N_{\mathrm{s}}\tau(1-\tau)^{2N_{\mathrm{s}}-1}(1-\mathrm{PER}). \tag{13}$$

Because sensors transmit using half of the transmission time, the access probability of sensors in the hierarchical cluster system increases by two times when compared to that of sensors in the cluster-based system, while the packet generation rate is fixed. Thus, the access probability of a CH is represented by

$$\tau_{\mathrm{c}} = P^{\mathrm{s}}_{\mathrm{suc}} 2\tau. \tag{14}$$

Conversely, in the complete control or the spatial reuse superframe schemes, the effect of the transmission of sensors on the nearby cluster is avoided; however, the transmission time of each cluster is reduced and equal to $1/2k$. Note that in the case of the complete control scheme, $k = N_{\mathrm{c}}$. Consequently, the transmission success probability and access probability of the complete control and spatial reuse superframe schemes are described as:

$$\begin{aligned} P^{\mathrm{s}}_{\mathrm{suc}} &= N_{\mathrm{s}}\tau(1-\tau)^{N_{\mathrm{s}}-1}(1-\mathrm{PER}), \\ \tau_{\mathrm{c}} &= P^{\mathrm{s}}_{\mathrm{suc}} 2k\tau. \end{aligned} \tag{15}$$

3.2.2 | In the second time slot

For any control scheme, in the second time slot, CHs forward the received packet to the coordinator while all sensors are sleeping. Therefore, CHs and the coordinator can be considered as a one-hop star system. The transmission success probability and the idle probability are, respectively, depicted as:

$$\begin{aligned} P^{\mathrm{c}}_{\mathrm{suc}} &= N_{\mathrm{c}}\tau_{\mathrm{c}}(1-\tau_{\mathrm{c}})^{N_{\mathrm{c}}-1}(1-\mathrm{PER}), \\ P^{\mathrm{c}}_{\mathrm{idle}} &= (1-\tau_{\mathrm{c}})^{N_{\mathrm{c}}}. \end{aligned} \tag{16}$$

Moreover, the throughput calculation method of the hierarchical cluster system is similar to that of the cluster-based system with a transmission time of $1/2$ and is represented by

$$C = \frac{1}{2}\frac{P^{\mathrm{c}}_{\mathrm{suc}} R_{\mathrm{code}} E[P]}{P^{\mathrm{c}}_{\mathrm{idle}} T_{\mathrm{s}} + P^{\mathrm{c}}_{\mathrm{suc}} T + P^{\mathrm{c}}_{\mathrm{fail}} T_{\mathrm{c}}}. \tag{17}$$

4 | CALCULATION RESULT

The hierarchical cluster scheme was proposed and the combination of the proposed scheme and other control schemes with the existence of BER was discussed. The throughput of the three control schemes was calculated and their comparisons with each other are presented in this section. The parameters of the system model are summarized in Table 1; the channel model between sensors is assumed to be additive white Gaussian noise, and MATLAB was used to calculate the throughput using the derived equations: (6), (9), (12), and (17).

The throughput depends on the SNR, total number of sensors, number of clusters, access probability, and so on; thus, the changes in throughput based on variation of each factor are described in the following section.

4.1 | Based on signal-to-noise ratio

In this work, BER and PER are taken into consideration; initially, the effect of SNR on the throughput is discussed.

TABLE 1 Parameters of the physical layer

Frequency band (MHz)	2400–2483.5
Packet component	Physical layer service data unit (PSDU) Modulation DBPSK
Symbol rates R_{s} (ksps)	600
Data rates for physical layer convergence protocol R_{PLCP} (kbps)	91.9
Data rates for PSDU R_{PSDU}(kbps)	242.9
Minimum contention windows $\mathrm{CW}_{\mathrm{min}}$ (slots)	16
Maximum contention windows $\mathrm{CW}_{\mathrm{max}}$ (slots)	64
Clear channel assessment time T_{ACC}	$63/R_s$
MAC header (bits)	56
MAC footer (bits)	16
Short interframe spacing time T_{sifs} (μs)	50
Preamble (bits)	88
Delay α (μs)	1

TABLE 2 Parameters for evaluating effects of signal-to-noise ratio (SNR)

SNR (dB)	Vary from 1 to 10
Total number of sensors (N)	100
Number of clusters (N_{c})	25
Payload ($E[P]$) (bytes)	100
Access probability (τ)	0.3

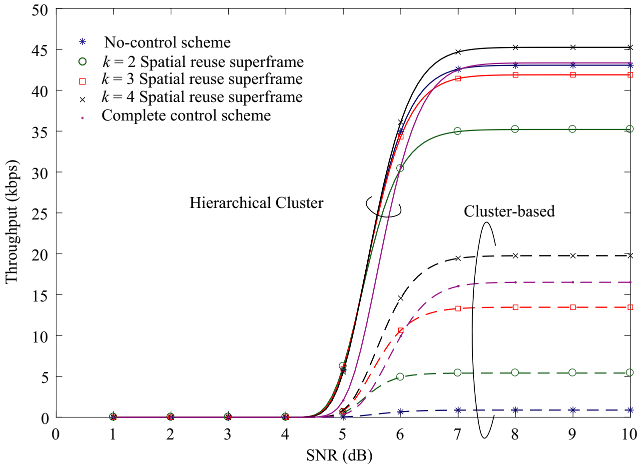

FIGURE 3 Throughput based on SNR

The parameters for evaluating the effect of SNR are listed in Table 2 and the calculation result is illustrated in Figure 3. The throughputs of the cluster-based and one-hop star topology systems were compared in a previous research [14]; thus, in this work, we only compared the throughputs of the cluster-based and hierarchical cluster systems. The calculation result indicates that the hierarchical cluster system outperforms the cluster-based system. This is because the hierarchical cluster system can avoid the twofold effects of the transmission of every packet on all sensors and the CH in the same cluster owing to the separation of the transmissions of sensors and the CH into different time slots. However, in each scheme, the throughput of all the control schemes is very small in the low SNR region and increases when the SNR increases. Especially, when the SNR exceeds 8 dB, the throughput is approximately constant; this means that the received packet is successfully decoded at the CH and coordinator and the value of PER ≈ 0. To evaluate clearly the effect of other parameters, for the subsequent calculations, SNR was set at 10 dB.

4.2 | Based on number of clusters

We assumed that the number of clusters varies from 2 to $N/2$, and the other parameters are as summarized in Table 3. The calculation result is shown in Figure 4.

TABLE 3 Parameters for evaluating the effect of the number of clusters

SNR [dB]	10
Total number of sensors (N)	100
Number of clusters (N_c)	Vary from 2 to $N/2$
Payload ($E[P]$) (bytes)	100
Access probability (τ)	0.3

The throughput of the spatial reuse superframe scheme is the highest when the number of clusters is small; however, the throughput of the complete control scheme demonstrates the highest value when the number of clusters increases. Moreover, for a higher number of spatial reuse superframes, a higher throughput is achieved. For each number of spatial reuse superframes, there is an optimal number of clusters for which the throughput achieves the highest value. This is because when the number of clusters is small, meaning the number of sensors in each cluster is large, an over concentration occurs at the CH. Whereas, when the number of the clusters is large, an over concentration occurs at the coordinator; this results in a small value of throughput. Therefore, there is an optimal number of clusters that creates a balance while transmitting data packets to the CHs and coordinator; therefore, the throughput is the highest at this number. According to the number of spatial reuse superframes, the total number of sensors, and the control scheme, the optimal number of clusters is changed.

4.3 | Based on access probability

The parameters for evaluating the effect of this feature are listed in Table 4, and the relation between the throughput and the access probability is illustrated in Figure 5.

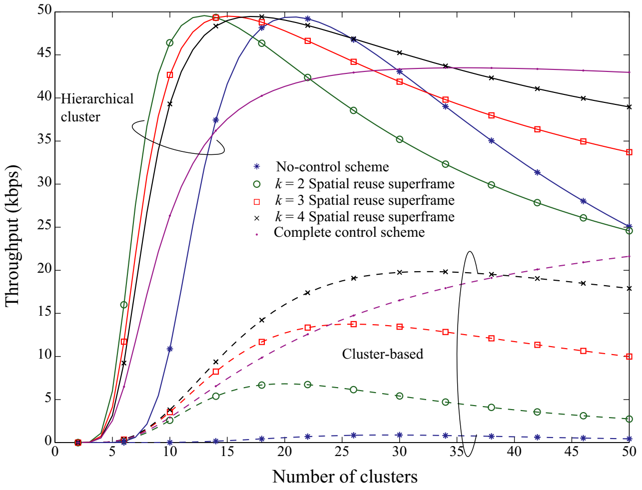

FIGURE 4 Throughput based on the number of clusters

TABLE 4 Parameters for evaluating the effects of access probability

SNR (dB)	10
Total number of sensors (N)	100
Number of clusters (N_c)	25
Payload ($E[P]$) (bytes)	100
Access probability (τ)	Vary from 0.001 to 0.2

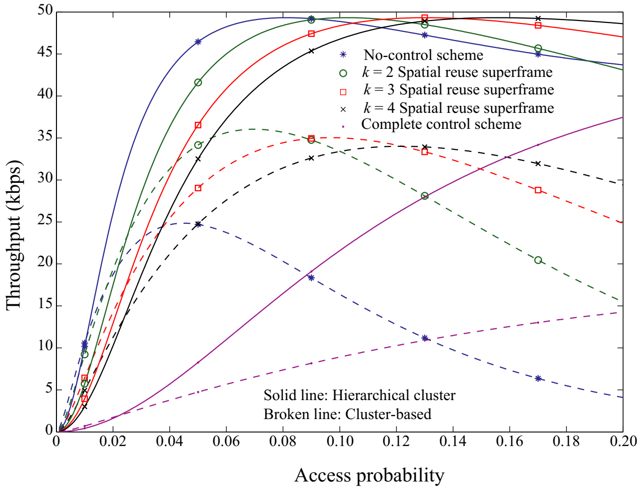

FIGURE 5 Throughput based on access probability

As shown in Figure 5, the throughput increases when τ increases because many packets are carried to the coordinator. However, similar to the effect of the number of clusters, there is an optimal value of τ that achieves the highest throughput. The reason is that when τ is higher than the optimal value, collisions occur at CHs; then, CHs have no data to transfer to the coordinator (τ_c decreases). As a result, the throughput of the system starts decreasing when τ exceeds the optimal value. Conversely, the optimal value of τ is changed according to k and other parameters, that is, the SNR, access probability, total number of sensors, number of clusters, and payload; moreover, the optimal value of k that achieves the maximal throughput is changed owing to the value of τ; thus, the optimal value of k increases corresponding to the increase in the value of τ. It means that when the access probability of sensors increases, the number of clusters in the same superframe should be reduced to avoid a collision, especially at the coordinator. When compared to the no-control and complete control schemes, the throughput of the spatial reuse superframe scheme is much higher.

4.4 | Based on the total number of sensors

If the number of clusters is fixed, the number of sensors in every cluster increases with the increase in the total number of sensors; consequently, over concentration occurs at a CH when the number of sensors in every cluster is high. Therefore, the number of clusters is assumed to be changed according to the total number of sensors. For a sample evaluation, we considered $N_c = N/5$, which implies that there are five sensors in every cluster. The parameters for evaluating effects of the total number of sensors are listed in Table 5 and the result is represented in Figure 6.

TABLE 5 Parameters for evaluating the effects of the total number of sensors

SNR (dB)	10
Total number of sensors (N)	Vary from 10 to 200
Number of clusters (N_c)	$N/5$
Payload ($E[P]$) (bytes)	100
Access probability (τ)	0.3

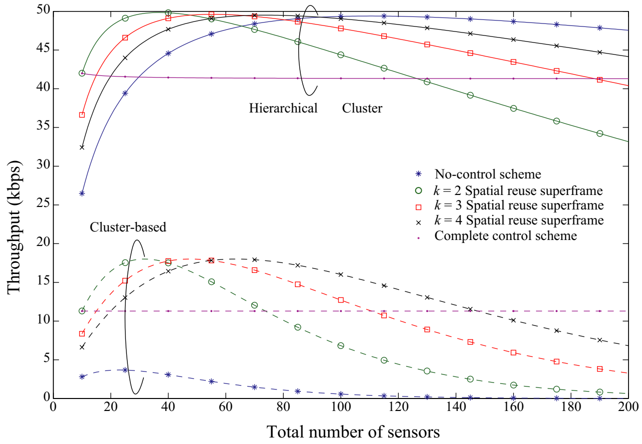

FIGURE 6 Throughput based on the total number of sensors

The number of clusters increases with the increase in the total number of sensors; moreover, as explained in Section 4.2, there is an optimal value for the number of clusters, meaning that there is an optimal total number of sensors that achieves the maximal throughput for every k of the spatial reuse superframe scheme. However, the number of sensors in each cluster is the same; thus, τ_c of the complete control scheme is fixed. Furthermore, as described in (9), the number of CHs is inversely proportional to the allocation transmission time of each cluster; consequently, the throughput of the complete control scheme is constant while the total number of sensors that indicate the number of clusters is changing. Conversely, the throughput of the spatial reuse superframe scheme can be much higher than that of other control schemes if the appropriate value of k is chosen.

4.5 | Based on the payload

The parameters for this scenario are listed in Table 6 and the effect of payload on throughput is illustrated in Figure 7.

TABLE 6 Parameters for evaluating the effects of payload

SNR (dB)	10
Total number of sensors (N)	100
Number of clusters (N_c)	25
Payload ($E[P]$) (bytes)	Vary from 0 to 250
Access probability (τ)	0.3

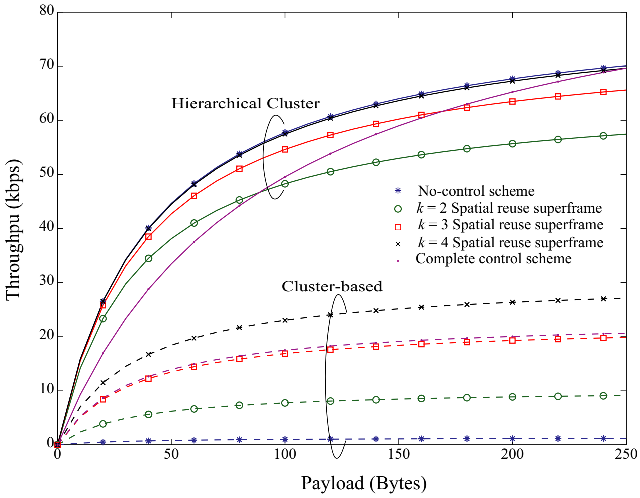

FIGURE 7 Throughput based on the payload

As shown in Figure 7, the throughput of all the control schemes increases when the payload increases. However, the variation of throughput according to the control schemes depends on the concrete model. The hierarchical cluster system still has a higher throughput than the cluster-based system.

5 | CONCLUSION

In this work, we analyzed the cluster-based WBAN considering the existence of BER in the system, derived the equations to calculate the probabilities, and then the throughput of the system. The hierarchical cluster was proposed and combined with the complete control and spatial reuse superframe schemes to improve the performance of the cluster-based WBAN. The proposed method was analyzed and compared to the cluster-based method considering several factors, that is, the SNR, access probability, total number of sensors, number of clusters, and payload. There is an optimal value for the number of clusters and optimal access probability that achieves the maximal throughput; moreover, the throughput of the proposed system is much higher than that of the cluster-based system for any control scheme. However, the transmission of all CHs and sensors in the proposed system should be controlled strictly; hence, the proposed hierarchical cluster is more complicated, especially in combination with the spatial reuse super-frame scheme.

The proposed hierarchical cluster, however, achieves a simple model where sensors and CHs transmit in the first and second time slots, respectively. Furthermore, the control of transmission was applied only to the sensors in the first time slot; the transmissions of CHs were uncontrolled. A more efficient hierarchical scheme and control method will be proposed in the future work. In addition, the throughput was used to evaluate the proposed system; other parameters, such as delay, energy efficiency, were not taken into consideration. This is the target of our future work.

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