Control superframe for High Throughput of Cluster-Based WBAN with CSMA/CA

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***Abstract*—Due to rapidly increasing of elderly population all over the world and quickly developing of entertainment devices, wireless body area network (WBAN) attracts attention. For both medical and non-medical applications, a reliability, high energy-efficiency and high throughput of WBAN communication are requested. The well-known cluster-based is proposed to obtain the high energy-efficiency, however the transmission in every cluster is controlled on MAC layer by superframe in order to obtain the high throughput. The performance of original cluster-based, complete control and spatial reuse superframe scenarios is analyzed and compared. The calculation result indicates that the spatial reuse superframe outperforms the original cluster-based when the access probability and/or the total number of sensors are high. Furthermore, there are the optimal number of clusters, the access probabilities and the total number of sensors that achieve the highest throughput. The optimization method of number of spatial reuse superframe (k) is proposed to obtain the highest throughput when another factors change. k increases when another factors of system model increase, excepted the payload. The optimization method of another factors is similar and the proposed method can be applied to not only IEEE802.15.6 WBAN but also another cluster-based wireless sensor networks.**

***Index Terms*—Cluster-based WBAN, standard IEEE802.15.6, spatial reuse superframe, control on MAC layer, maximize throughput, number of clusters, total number of sensors, access probability.**

I. Introduction

Due to rapidly increasing of elderly population all over the world and quickly developing of entertainment devices, body area network (BAN) attracts attention. The WBAN consists of many sensors and a coordinator that are placed in, on or around body. For both medical and non-medical applications, a reliability, high energy-efficiency and high throughput of WBAN communication are requested. There are many researches on WBAN based on standard IEEE802.15.6 [1]-[4]. The physical (PHY) layer, media access control (MAC) layer and network layer are analyzed separately [5] and in crosslayer[6]. Most of them focus on wearable sensor system, however implant sensor system [7] and remote system [8] are discussed. The tradeoff of throughput and life time of WBAN system was indicated in these researches, it is similar to another system. However, because of unexchangeable of batteries, the life time WBAN should be seriously considered, especially for implant sensors. In order to reduce a consumption power meaning extend the life time of WBAN system, a cluster-based WBAN is take into consideration.

There are many researches on the cluster-based, such as wireless sensor network, ad hoc network and so on. However, as the best of our knowledge, the cluster-based WBAN haven't been discussed in any literature. The cluster-based is well known as an effective way to reduce the energy consumption of wireless sensor networks. Its main idea is to select a subset of sensors to be cluster heads (CHs) for a given wireless sensor network. Hence, data which generated at member sensors can be sent to the coordinator via CHs. There are many popular mechanisms, i.e. LCA [9], LEACH [10], HEAD [11], EAP [12] etc. In order to extend lifetime of system, new routing mechanisms have been proposing [13], [14], [15]. Moreover, a multiple hops algorithm [16] and a hierarchical clustering [17] were proposed to improve performance of cluster-based system. However, these researches focussed on energy-efficiency, the throughput wasn't discussed. In this paper, we analyze only the throughput of cluster-based WBAN based on standard IEEE802.15.6.

Since the transmission topology of IEEE802.15.6 was decided as star plus one, the multiple-hop cluster-based and the hierarchical cluster can't be applied to cluster-based WBAN system, only the original routing mechanism of two hops can be applied to WBAN system. Furthermore, all sensors generate a vital data packet and transmit forward the coordinator via CHs, an overconcentration at the coordinator is expected to be avoided. Therefore, the throughput is improved, especially when the number of sensors and/or the access probability are high. On the other hand, because of high flexibility and extensibility of carrier sense multiple access /collision avoidance (CSMA/CA), it is adopted in IEEE802.15.6 and considered as practical algorithm. However, in cluster-based WBAN with CSMA/CA, CHs forward the received vital data packet to the coordinator, hence the coordinator and member sensors (included member sensors of nearby clusters) are affected twice by transmission of one data packet. It is a reason of decreasing throughput of system, especially if a packet arrive rate of sensors is high. In order to increase the throughput of system, the transmission of each cluster is controlled in every superframe. It means that in a superframe, one or several clusters (their member sensors and CH) are allowed to transmit a data packet, other clusters keep silent. The number of clusters that are allowed to transmit in a superframe affects to the performance of system. If it is small meaning the smallest number of superframes in which all clusters have been allowed to transmit is large. Therefore, the normalized duration of superframe becomes greatly small, and then the

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normalized throughput is low. Consequently, the spatial reuse superframe is proposed to increase the number of clusters that are allowed to transmit in a superframe. We define that the smallest number of superframes in which all clusters have been allowed to transmit is as number of spatial reuse superframes. Its dependance on factors of system model are represented and it is optimized to obtain the highest throughput.
The rest of paper is organized as follows. We introduce a brief standard IEEE802.15.6 and system model of cluster-based WBAN in Section II. The original cluster-based as well as the spatial reuse superframce for control on MAC layer are analyzed in Section III. The optimization method of number of spatial reuse superframes is proposed and discussed in Section IV. Finally, Section V concludes the paper.

II. Cluster-based WBAN system

A. Brief of IEEE802.15.6

Since the CSMA/CA is considered in our analysis, the basic procedures of this protocol is explained as defined in the standard.

TABLE I
Contention window bound for CSMA/CA

User priority	W_{min}	$W_{\max}$
0	16	64
1	16	32
2	8	32
3	8	16
4	4	16
5	4	8
6	2	8
7	1	2

In CSMA/CA procedure , a sensor sets its backoff counter to a random integer number uniformly distributed over the interval [1,W] where $W \in (W_{min}, W_{max})$ denotes contention window. The values of W_{min} and W_{max} change depending on the user priorities (UPs) as given in Table I. The sensor decreases its backoff counter by one for each idle CSMA slot of duration. Particularly, the sensor treats a CSMA slot to be idle if it determines that the channel has been idle between the start of the CSMA slot and $pCCATime$. If the backoff counter reaches zero, the sensor transmits data packet. If the channel is busy because of transmission of another sensor, the sensor locks its backoff counter until the channel is idle. The W is doubled for even number of failures until it reaches W_{max}. The failure means that the sensor fails to receive an acknowledgement from the coordinator.
The service time is defined as total time to transmit a packet included the backoff time (T_W), the time to transmit a data (T_{data}), interframe spacing (T_{pSIFS}), the time of acknowledgement packet (T_{ACK}) and delay time (α).

$$T = T_W + T_{DATA} + T_{ACK} + 2T_{pSIFS} + 2\alpha. \quad (1)$$

According to the standard and the value of W_{min}, W_{max} shown in Table I, the value of the average backoff time can be obtained as

$$T_W = \begin{cases} \frac{W_{min}T_s}{2} + P_{col}^2 W_{min}T_s + P_{col}^4 \frac{W_{max}T_s}{2} & \text{for even UPs,} \\ \frac{W_{min}T_s}{2} + P_{col}^2 \frac{W_{max}T_s}{2} & \text{for odd UPs,} \end{cases} \quad (2)$$

here, P_{col} is the collision probability.

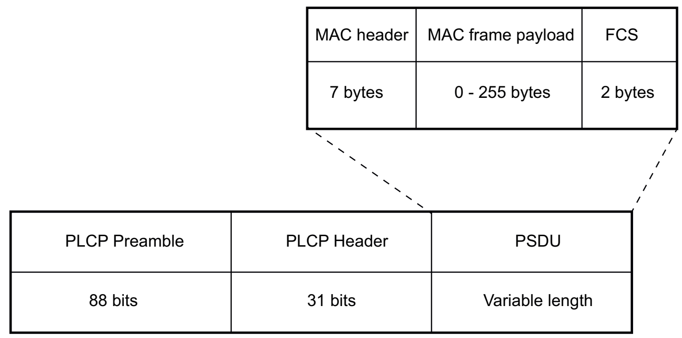

Fig. 1. IEEE802.15.6 PPDU structure

The Narrowband (NB) PHY is responsible for activation/deactivation of the radio transceiver, Clear Channel Assessment (CCA) within the current channel and data transmission/reception. The Physical Protocol Data Unit (PPDU) frame of NB PHY contains a Physical Layer Convergence Procedure (PLCP) preamble, a PLCP header, and a PHY Service Data Unit (PSDU) as given in Figure 1. Since a data packet consists of a preamble, physical header, MAC header, MAC frame body and frame check sequence, the time to transmit a data packet is represented as follows.

$$T_{DATA} = T_P + T_{PHY} + T_{MAC} + T_{BODY} + T_{FCS}, \quad (3)$$

here T_P, T_{PHY}, T_{MAC}, T_{BODY}, T_{FCS} represent the time to transmit a preamble, physical header, MAC header, MAC frame body and frame check sequence, respectively. Let's R_s, R_{hdr} and $E[P]$ denote respectively the symbol rate, the data rate and the payload, hence T_{DATA} becomes as

$$\begin{aligned} T_{DATA} &= \frac{\text{Preamble} + \text{PHY header}}{R_s} \\ &+ \frac{8(\text{MAC header} + \text{E[P]} + \text{MAC footer})}{R_{hdr}}. \end{aligned} \quad (4)$$

Since an immediate acknowledgement carries no payload, its transmission time is given by

$$\begin{aligned} T_{ACK} &= T_P + T_{PHY} + T_{MAC} + T_{FCS}, \\ &= \frac{\text{Preamble} + \text{PHY header}}{R_s} \\ &+ \frac{8(\text{MAC header} + \text{MAC footer})}{R_{hdr}}. \end{aligned} \quad (5)$$

The parameter of standard IEEE802.15.6 that used in this paper is summarized in Table II.

TABLE II
IEEE802.15.6 PPDU PARAMETER

Symbol rate [ksps]	600
Data rate [kbps]	242.9
Clear channel assessment [bits]	63
MAC header [bits]	56
MAC footer [bits]	16
Minimum interframe spacing time [μs]	20
Short interframe spacing time T_{sifs}[μs]	50
Preamble [bits]	88
PHY header [bits]	31
Propagation delay [μs]	1

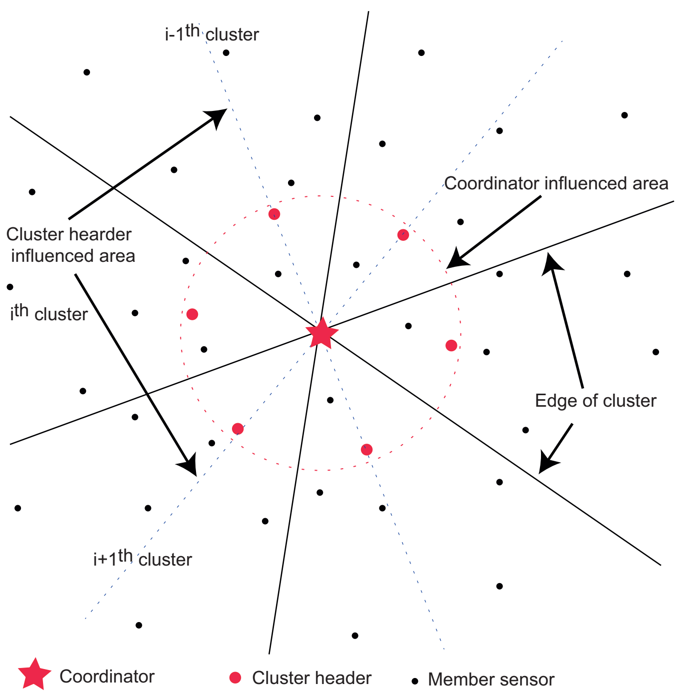

Fig. 2. Cluster model for WBAN

B. System model of cluster-based WBAN

The cluster-based WBAN is represented in Figure 2. The coordinator is placed in the center of body and sensors are uniformly distributed in, on or around body. CHs is assumed to be placed for transferring the received data packet, they don't generate vita data by themselve, moreover they either transmits or receives a packet in the same time. CHs can be placed following some algorithms, i.g. LEACH, HEED, EAP and so on. However, in any algorithm, CHs should be placed between almost member sensors and the coordinator as described in Figure 2 for high energy-efficiency. A CH is affected by not only its member sensors, but also the CHs and member sensors of nearby clusters. In Figure 2, six CHs meaning six clusters are described and they are separated by edge of cluster. Two CHs and a half of member sensors which are located within cluster header influenced area of $(i-1)^{th}$ and $(i+1)^{th}$ clusters affects to the CH of i^{th} cluster. Moreover, the coordinator is affected by all CHs and member sensors that locate close to.

The transmission in this system is assumed to be operated by CSMA/CA scheme due to the flexibility and the extensibility of CSMA/CA. However, the transmission of every cluster is controlled by superframe which is separated by beacon. The coordinator decides the duration of superframe and allocates that which cluster should transmit in which superframe. UP of all sensors in the system is assumed to be the same as zero and the access probability of all sensors, the number of member sensors in each cluster are assumed to be the same. A sensor can access the channel by its access probability τ that can be calculated from its packet arrive rate by Discrete Time Markov Chains (DTMC) method [18], whereas the packet arrive rate also can be derived from access probability by the same method. In this paper, the access probability is dealt. Let's N_s, N_c and N_h denote the number of member sensors in a cluster, the number of CHs and the number of member sensors that affect to the coordinator, respectively. The total number of sensors (excepted CHs) is represented as N, and then $N_s = \frac{N}{N_c}$. Under the condition that sensors are uniformly distributed and they can control their transmit power, the number of sensors close to the coordinator is dependent on the position of CHs. As explained above, CHs is located between almost member sensors and the coordinator, thus a ratio of distance between a CH and the coordinator, the coordinator and the farthest member sensor is considered as approximately $\frac{1}{3}$. Therefore, the N_h is calculated by

$$N_h = N\frac{\pi(\frac{1}{3})^2}{\pi 1^2} = \frac{N}{9}. \tag{6}$$

The N_h is an approximate value, however all scenarios are compared fairly and the relative result is independent on this value.

III. Cluster-based WBAN with spatial reuse superframe

A. Original cluster-based for WBAN

The original cluster-based that isn't controlled on MAC layer by superframe is discussed in order to evaluate the proposed spatial reuse superframe. In the original cluster-based WBAN, the access probability of CHs can be calculated as follows.

$$\tau_c = P^s_{suc}\tau, \tag{7}$$

here P^s_{suc} denotes the successful probability of all member sensors in a cluster. A member sensor transmits successfully when all member sensors in cluster header influenced area as well as three CHs keep silent.

$$P^s_{suc} = N_s\tau(1-\tau)^{N_s-1}(1-\tau_c)^3(1-\tau)^{2\frac{N_s}{2}}. \tag{8}$$

Since $\tau, \tau_c \ll 1$, more than three of multiplication of τ and/or τ_c can be neglected. Thus, the access probability of CHs is represented as follows.

$$\tau_c = \frac{N_s\tau^2(1-\tau)^{2N_s-1}}{1+3N_s\tau^2(1-\tau)^{2N_s-1}}. \tag{9}$$

As system model described above, the CH transmit successfully when other CHs and N_h member sensors close to the coordinator keep silent. Moreover, the CH senses that the channel is idle when all CHs and all member sensors in cluster header influenced area keep silent. Therefore, the successful probability and the idle probability of every CH are respectively represented by

$$\begin{aligned} P^c_{\text{suc}} &= \tau_c(1-\tau_c)^{N_c-1}(1-\tau)^{N_h}, \\ P^c_{\text{idle}} &= (1-\tau_c)^{N_c}(1-\tau)^{2N_s}. \end{aligned} \tag{10}$$

Let's $P^c_{col} = 1 - P^c_{\text{suc}} - P^c_{\text{idle}}$ denote the collision probability of the channel when there are one or more another sensors/CHs access the channel. However, after transmitting a data packet, the sensor/CH waits for ACK packet from the CH/coordinator. In case of collision, there is no ACK packet replied to the sensor/CH, and then the sensor/CH resets its backoff counter for retransmission. It means the service time T and the collision time T_c are almost the same. The throughput of system is described as follows.

$$Thro = \frac{N_c P^c_{\text{suc}} E[P]}{P^c_{\text{idle}} T_s + P^c_{\text{suc}} T + P^c_{bus} T_c}. \tag{11}$$

B. WBAN with spatial reuse superframe

As explained in Sec. I, in the original cluster-based WBAN, member sensors and CHs (included the ones of nearby clusters) are affected twice by transmission of one packet. Therefore, in order to increase the throughput of system, the control on MAC layer is proposed. The coordinator assign every cluster to transmit in different superframe that is separated by beacon. It means that in this scenario, the number of spatial reuse superframes is equal to the number of clusters. We assume that the length of all superframes is the same. Since all member sensors and the CH of a cluster transmit in its own superframe, the successful probability of all member sensors in a cluster, the successful probability and the idle probability of every CH are changed as

$$\begin{aligned} P^s_{suc} &= N_s \tau (1-\tau)^{N_s-1}(1-\tau_c), \\ P^c_{\text{suc}} &= \tau_c(1-\tau_c)^{N_c-1}(1-\tau)^{\frac{N_h}{N_c}}, \\ P^c_{\text{idle}} &= (1-\tau_c)(1-\tau)^{N_s}. \end{aligned} \tag{12}$$

The access probability of CHs in this scenario can be obtained easily.

$$\tau_c = \frac{N_s \tau^2 (1-\tau)^{N_s-1}}{1 + N_s \tau^2 (1-\tau)^{N_s-1}}. \tag{13}$$

This scenario is called as complete control scenario. Let's compare the successful probability of all member sensors in complete control scenario (eq. 12) to that in the original cluster-based (eq. 8), the former one is much higher. It is similar to the successful probability of CH. However, each cluster transmits in a superframe whose duration is N_c times smaller than duration of superframe in original cluster-based. Consequently, the throughput of system is divided by N_c.

$$Thro = \frac{P^c_{\text{suc}} E[P]}{P^c_{\text{idle}} T_s + P^c_{\text{suc}} T + P^c_{bus} T_c}. \tag{14}$$

In order to increase the throughput, the spatial reuse superframe is considered. More than one clusters are assigned to transmit in the same superframe. However, the neighbor cluster is assigned to different superframe. The number of clusters that assigned to each superframe is assumed to be the same as $\frac{N_c}{k}$, here k denotes the number of spatial reuse superframes. The probabilities and the throughput of spatial reuse superframe WBAN system are described as follows.

$$\begin{aligned} P^s_{suc} &= N_s \tau (1-\tau)^{N_s-1}(1-\tau_c), \\ P^c_{\text{suc}} &= \tau_c(1-\tau_c)^{\frac{N_c}{k}-1}(1-\tau)^{\frac{N_h}{k}}, \\ P^c_{\text{idle}} &= (1-\tau_c)^{\frac{N_c}{k}}(1-\tau)^{N_s}, \\ Thro &= \frac{N_c}{k} \frac{P^c_{\text{suc}} E[P]}{P^c_{\text{idle}} T_s + P^c_{\text{suc}} T + P^c_{bus} T_c}. \end{aligned} \tag{15}$$

The access probability of CHs in spatial reuse superframe is the same as (13).

C. Effect of number of clusters

We have described the system model and the throughput calculation method for spatial reuse superframe of WBAN in previous sections. However, the throughput of system depends on the total number of sensors, the number of clusters, the payload size (relates to the service time), the access probability and so on. The effect of each factor on the throughput is investigated when the other factors are fixed. The system model is the same as explained above and the parameter in Table. II is used. We show the relation between the throughput and total number of sensors based on different number of spatial reuse superframe. The original cluster-based and the complete control scenarios can be considered as $k = 1$ and $k = N_c$ spatial reuse superframe scenario. The number of clusters is varied from 2 to $\frac{N}{2}$ and the other parameters are fixed as summarized in Table. III. The throughput of system that corresponded to variation of number of clusters is shown in Figure 3. As expected, the throughput of spatial reuse superframe scenario is higher than that of original cluster-based and complete control scenarios. However, the higher the number of spatial reuse superframe (k) is, the higher the throughput is. Additionally, there are the optimal number of clusters that achieves the highest throughput. It can be explained that when the number of clusters is smaller than optimal value meaning the number of member sensors in each cluster is large, so that the overconcentration at the CH is occurred and the access probability of CH decreases, as a result, the throughput of system is low. On the contrary, when the number of clusters is larger than the optimal value, the

TABLE III
PARAMETERS FOR EFFECT OF NUMBER OF CLUSTER

Total number of sensors (N)	100
Number of clusters (N_c)	vary from 2 to $\frac{N}{2}$
Payload size ($E[P]$) [byte]	100
Access probability (τ)	0.3

overconcentration at the coordinator is occurred and then the throughput also is low. According to the k, the total number of sensors and the system model, the optimal number of clusters are changed. Since the complete control scenario can be considered as $k = N_c$ spatial reuse superframe scenario, it is estimated that there is the optimal number of clusters for complete control scenario when the number of sensors and the number of clusters are high enough. The relation of throughput

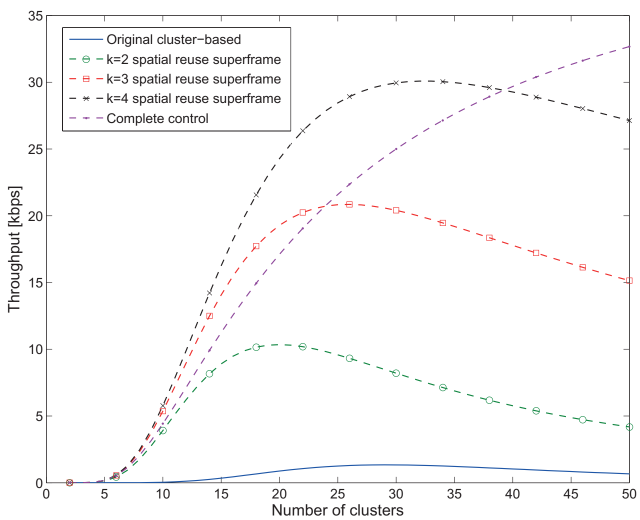

Fig. 3. Effect of number of clusters on throughput

and other factors is similar and discuss in the next section.

IV. Optimizing number of spatial reuse superframes

As described in the previous section, there are the optimal number of spatial reuse superframes depending on total number of sensors, access probability, number of clusters and payload. Therefore, optimization of k for the system model is important to obtain the highest throughput. This method can be applied to any cluster-based system model. Furthermore, the optimization method of k is similar to other factors, i.e. the number of clusters, the total number of sensors and the access probability. Consequently, only optimization method of k is represented, the optimization method of other factors is straightforward.

A. Optimization method of k

From (15), the throughput of system is represented as follows. Notice that the collision time is assumed to be the same as the service time.

$$Thro = \frac{N_c}{k}\frac{P^c_{\text{suc}}E[P]}{P^c_{\text{idle}}(T_s - T) + T}. \tag{16}$$

Let

$$Invthro = \frac{k}{N_c}\frac{P^c_{\text{idle}}(T_s - T) + T}{P^c_{\text{suc}}}, \tag{17}$$

so that the throughput is maximized when the function $invthrou$ is minimized.

Under the condition $\tau,\ \tau_c < 1$, the component containing $\tau^3,\ \tau_c^3$ or over can be neglected. Hence, the approximation

$$(1-\tau)^p \approx 1 - p\tau + \frac{p(p-1)}{2}\tau^2, \tag{18}$$

holds. By solving the term $\frac{\partial Invthro}{\partial k} = 0$, k is optimized. From $\frac{\partial Invthro}{\partial k} = 0$, we have

$$(a_1 + b_1)k^2 + (a_2 + b_2)k + a_3 + b_3 = 0, \tag{19}$$

here

$$\begin{aligned}
a_1 &= (T_s - T)(1 + \tau_c - 2\tau_c^2), \qquad (20)\\
a_2 &= (T_s - T)(-2N_s\tau - \frac{7}{2}N_c\tau_c - N_s\tau^2 - 2N_s\tau\tau_c\\
&\quad - \frac{3}{2}N_c\tau_c^2 + 3\tau_c^2 - 2N_cN_s\tau\tau_c^2),\\
a_3 &= (T_s - T)(2N_s^2\tau^2 + 6N_sN_c\tau\tau_c + 2N_c^2\tau_c^2);\\
b_1 &= T(1 + \tau_c + \tau_c^2),\\
b_2 &= T(-2N_s\tau - N_s\tau^2 - 2N_c\tau_c - 2N_s\tau\tau_c - 6N_c\tau_c^2),\\
b_3 &= T(\frac{3}{2}N_s^2\tau^2 + \frac{3}{2}N_c^2\tau_c^2 + 3N_cN_s\tau\tau_c).
\end{aligned}$$

It is easy to recognize that there are two solutions of k, however k should be a positive integer. Thus, only one solution satisfies.

$$k = \text{floor}\left(\frac{-(a_2 + b_2) + \sqrt{\Delta}}{2(a_1 + b_1)}\right), \tag{21}$$

here $\Delta = (a_2 + b_2)^2 - 4(a_1 + b_1)(a_3 + b_3)$ and floor(m) denotes a function that rounds m to the nearest integer less than or equal to m.

B. Numerical evaluation

The optimal value of k is described in Figure 4 based on changing of every factor, i.e. the number of clusters, the access probability, the total number of sensors and the payload. In Figure 4, the horizontal axis shows the changing of each factor separately, and the vertical axis is common and shows the optimized k. As described in Figure 4, the optimized k increases when another factors increase, excepted the payload. The optimal k is fixed as 7 when the payload is changed. The reason of increasing optimized k is the same as explained in previous section. The reason of fixing optimized k when the payload changes is explained as follows. As represented in (20), there is the service time (T) in both a_i and b_i, $\text{i} = 1, 2, 3$, however the positive value of T in b_i is almost the same as the negative value of T in the corresponded a_i. Therefore, the service time meaning the payload doesn't affect to the optimal k.

V. Conclusion

In this paper, we have analyzed the performance of cluster-based WBAN system with CSMA/CA scheme based on standard IEEE802.15.6. Since the energy-efficiency has been discussing on many literatures, in this paper, we focused

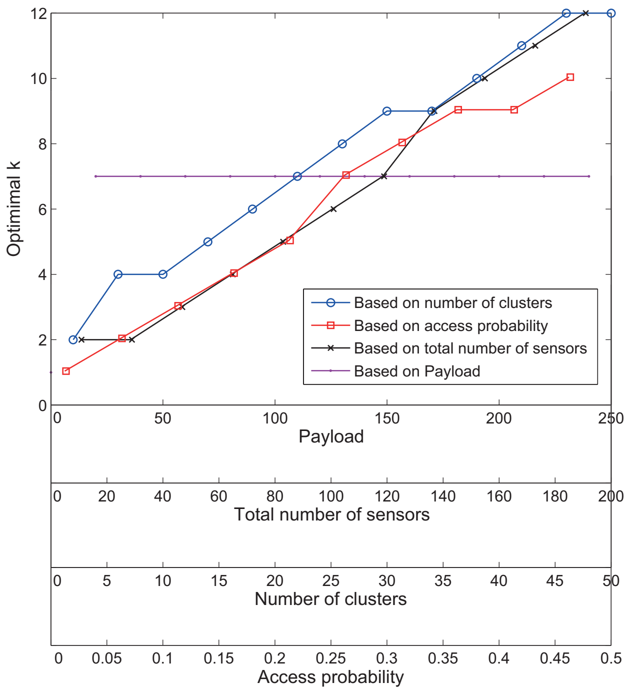

Fig. 4. optimized k based on every factor

on the throughput, especially in the high access probability range. The calculation method of throughput was represented for the original cluster-based, the spatial reuse superframe and the complete control scenarios. There are the optimal number of clusters, the access probabilities and the total number of sensors that achieve the highest throughput. However, the throughput increases when the payload increases. Consequently, in order to obtain the highest throughput, the optimization method of k was proposed and the optimization method of other parameters is straightforward. The numerical result indicates that the optimized k increases when another factors of system model increase, however it is constant when the payload is varied. The spatial reuse superframe was analyzed based on IEEE802.15.6, however the proposed method also can be applied to another systems.

In this paper, the UP of all sensors and the number of member sensors in each cluster were assumed to be the same. The system that has a commix of several UPs and/or a dynamic distribution of sensors is considered in the future works.

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