On Throughput and Power Consumption of Multiple-Hop WBANs

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***Abstract*—There have been increases in the elderly population worldwide, and this has been accompanied by rapid growth in the health-care market, as there is an ongoing need to monitor the health of individuals. Wireless body area networks (WBANs) consist of wireless sensors attached on or inside the human body to monitor vital health-related problems, e.g., electrocardiograms (ECGs), electroencephalograms (EEGs), and electronystagmograms (ENGs). With WBANs, patients' vital signs are recorded by each sensor and sent to a coordinator. However, because of obstructions by the human body, sensors cannot always send the data to the coordinator, requiring them to transmit at higher power. Therefore, we need to consider the lifetime of the sensors given their required transmit power. In the IEEE 802.15.6 standard, the transmission topology functions as a one-hop star plus one topology. In order to obtain a high throughput, we reduce the transmit power of the sensors and maintain equity for all sensors. We propose the multiple-hop transmission for WBANs based on the IEEE 802.15.6 carrier-sense multiple-access with collision avoidance (CSMA/CA) protocol. We calculate the throughput and variance of the transmit power by performing simulations, and we discuss the results obtained using the proposed theorems.**

***Index Terms*—Multiple-hop body area networks, system throughput, variance of transmit power, CSMA/CA based on IEEE802.15.6.**

I. INTRODUCTION

The performance of one-hop WBANs, where all sensors transmit directly to the coordinator, has been analyzed [1]-[3] However, in the one-hop star topology system, some sensors need to transmit their data at a higher power because the coordinator is not always close to all sensors. Therefore, the lifetimes of these sensors will decrease, and each sensor may interfere with other sensors nearby. Moreover, the link between the sensors and the coordinator may fail because of obstructions caused by the human body, especially when the person is moving. Therefore, a multiple-hop system has been proposed. In multiple-hop systems, because each sensor transmits its signal to the neighboring sensor, the transmit power, transmit area, and effective area are expected to be smaller than the corresponding values of one-hop systems. Therefore, the number of sensors that experience interference decreases, and the lifetimes of the sensors will increase. In addition, even if there is a failure in the direct link between the sensors and the coordinator fails, the sensor can transmit to the coordinator via other sensors that are also connected to it. Therefore, in this paper, we analyze multiple-hop WBAN systems.

Multiple-hop systems have been researched in many studies, e.g., ad hoc networks, mobile networks, and intelligent transport systems (ITS) [4]-[7]. However, these studies were based on different standards, i.e., IEEE 802.15.4, IEEE802.11, etc. Furthermore, in these systems, the sender(s) send the signal to the receiver(s) via relay(s), and the relay only forwards the signal. On the other hand, in WBAN systems, each sensor forwards the received signal while monitoring the status of the body and independently generating the vital data. In addition, in the IEEE 802.15.6 standard, the transmission topology is defined as a star-plus-one topology, and it is currently being revised. We therefore need to obtain a performance analysis of multiple-hop WBANs that are based on the IEEE 802.15.6 standard. We maximized the throughput of the one-hop star topology system, and we proved two lemmas to explain the performance of multiple-hop WBANs. We then compared the throughput and transmit power for one-, two-, three-, and four-hop systems.

The rest of the paper is organized as follows. In Section II we introduce the channel model of the one-hop star topology of WBANs and maximize the throughput of the one-hop star topology system. In section III, we prove two lemmas that explain the performance of multiple-hop WBANs. In Section IV, we describe multiple-hop WBANs and express the numerical evaluation in Section V. Finally, Section VI concludes the paper.

II. ONE-HOP STAR TOPOLOGY FOR WBANS

A. System model

Fig. 1 shows an example of a WBAN system. There are many sensors uniformly distributed around the body to monitor the health status of the individual, and each of the sensors transmits vital data signals to the coordinator. In a WBAN system based on the one-hop star topology, all of the sensors transmit their data directly to the coordinator. The data packets are generated at each sensor by its access probability. After receiving the information signal from the coordinator, the sensors can estimate the distance and channel condition between the coordinator and themselves. Thus, each sensor appropriately adjusts its transmit power in order to transmit the signal to the coordinator. The appropriate transmit power is determined such that the signal-to-noise ratio (SNR) at the receiver sites equals the threshold of the desired SNR ($dSNR_{\mathrm{thres}}$). The sensor senses that the channel is busy if

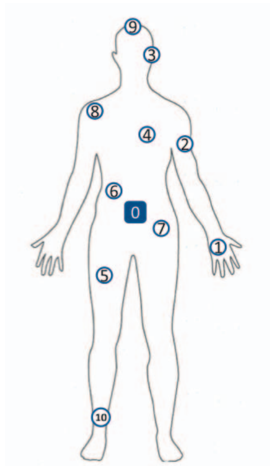

Fig. 1. WBAN channel model

the SNR of the received signal is higher than the threshold of the effective SNR ($eSNR_{\text{thres}}$). Normally, $dSNR_{\text{thres}} > eSNR_{\text{thres}}$. The transmission fails if the sensor fails to receive an immediate acknowledgement (I-ACK)

B. Performance analysis of one-hop star topology

The service time (T) is defined as the total time to transmit a packet, and includes the average backoff time (T_{CW}), the time to transmit a data packet (T_{DATA}), the interframe spacing (T_{pSIFS}), the time to receive an immediate acknowledgement packet (T_{ACK}), and the delay time (α).

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

T_{s} denotes the CSMA slot length. Hence, the average backoff time is given as follows [7].

$$T_{\text{CW}} = \frac{CW_{\min} T_{\text{s}}}{2}. \quad (2)$$

Because a data packet consists of a preamble (T_{P}), physical header (T_{PHY}), MAC header (T_{MAC}), MAC frame body (T_{BODY}), and frame check sequence (T_{FCS}), the time to transmit a data packet is given by.

$$T_{\text{DATA}} = T_{\text{P}} + T_{\text{PHY}} + T_{\text{MAC}} + T_{\text{BODY}} + T_{\text{FCS}}. \quad (3)$$

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

$$T_{\text{ACK}} = T_{\text{P}} + T_{\text{PHY}} + T_{\text{MAC}} + T_{\text{FCS}}. \quad (4)$$

C. Optimizing access probability

The number of sensors on the body is denoted by N, and each sensor randomly and independently accesses a slot time with probability τ. Based on this assumption, the probability, P_{idle}, that no sensor accesses a given slot is readily given by

$$P_{\text{idle}} = (1-\tau)^{\text{N}}. \quad (5)$$

Similarly, the probability, P_{suc}, that just one sensor accesses a given slot is expressed as

$$P_{\text{suc}} = N\tau(1-\tau)^{\text{N}-1}. \quad (6)$$

The collision time, T_{c}, , is defined as the duration of a period during which other sensors cannot access the channel because of the occurrence of a collision. However, as mentioned above, the sensor transmits the signal to the coordinator and waits for the ACK packet from the coordinator. In the case of a collision, no ACK packet is sent to the sensor, and the sensor then starts the countdown of its backoff time. This means that the service time, T, and the collision time, T_{c}, are almost the same. In this paper, we assume $T = T_{\text{c}}$. Because the system slot-time, T_{s}, elapses during an idle slot, we can derive the average slot duration as follows.

$$E[slot] = P_{\text{idle}}T_{\text{s}} + P_{\text{suc}}T + (1 - P_{\text{suc}} - P_{\text{idle}})T_{\text{c}}. \quad (7)$$

Finally, the system throughput, $Thro_{\text{s}}$, is given the average amount of information transmitted in each slot. Note that E[P] is the average MAC frame body size.

$$\begin{aligned} Thro_{\text{s}} &= \frac{P_{\text{suc}}E[P]}{E[slot]}, \quad (8) \\ &= \frac{P_{\text{suc}}E[P]}{P_{\text{idle}}T_{\text{s}} + P_{\text{suc}}T + (1 - P_{\text{suc}} - P_{\text{idle}})T_{\text{c}}}. \end{aligned}$$

The throughput above is maximized as long as we minimize the term:

$$f = \frac{P_{\text{idle}}(T_{\text{s}} - T) + T}{P_{\text{suc}}}. \quad (9)$$

The optimal value τ_{opti} that maximizes the throughput is given by the solution of the equality $\frac{\partial f}{\partial \tau} = 0$

$$(1-\tau_{\text{opti}})^{\text{N}} - \frac{T}{T_{\text{s}}}\left(N\tau_{\text{opti}} - (1-(1-\tau_{\text{opti}})^{\text{N}})\right) = 0. \quad (10)$$

Under the condition $\tau \ll 1$, the approximation

$$(1-\tau_{\text{opti}})^{\text{N}} \approx 1 - N\tau_{\text{opti}} + \frac{N(N-1)}{2}\tau_{\text{opti}}^2, \quad (11)$$

holds, and hence the optimal τ (τ_{opti}) can be found

$$\tau_{\text{opti}} = \frac{1}{N\sqrt{\frac{T}{2T_{\text{s}}}}}. \quad (12)$$

III. SUPPLEMENTARY THEOREMS

In this section, we explain some lemmas of one-hop star topology systems, after which we analyze the performance of multiple-hop WBANs. The system in which all sensors transmit their signal with the optimal access probability (τ_{opti}) is referred to as scheme 1, while scheme 2 refers to a system in which each sensor transmits with a different access probability. Let us assume that the total access probabilities of all sensors are fixed at τ_{total} for both schemes 1 and 2.

A. Lemma 1

In scheme 1, the system throughput increases when the number of sensors decreases, meaning that as the number of sensors decreases, the throughput increases.

From (12), the multiplication $N\tau_{\text{opti}}$ is fixed; this means that even if the number of sensors is changed, the total access probability of all sensors remains fixed if all sensors transmit

with the optimal access probability and $\tau_{\text{total}} = \sqrt{\frac{2T_\text{s}}{T}}$.
The function f is considered to be a function of the number of sensors. From (5), (6), (10) and (11), the function f is described as follows.

$$\begin{aligned} f &= \frac{(1-\tau)^{\text{N}}(T_\text{s}-T)+T}{N\tau(1-\tau)^{\text{N}-1}}, \qquad (13)\\ &= \frac{(T-T_\text{s})(1-\frac{\tau_{\text{total}}}{N})}{1-\tau_{\text{total}}}. \end{aligned}$$

Thus, when the number of sensors increases, the function f increases meaning that the throughput decreases.

B. Lemma 2

In the case where the number of sensors remains the same, the throughput of scheme 2 is higher than that of scheme 1, which means that the throughput of the system with different access probabilities is higher than that of the system with the same access probability.
In a system with different access probabilities, the idle probability and the successful probability in (5), (6) are changed as follows.

$$P_{\text{idle}} = \prod_{i=1}^{N}(1-\tau_\text{i}), \qquad (14)$$

$$P_{\text{suc}} = \sum_{i=1}^{N}\tau_\text{i}\prod_{j\neq i}^{N}(1-\tau_\text{j}), \qquad (15)$$

where τ_i denotes the access probability of sensor i. We have

$$(1-\tau_1)+(1-\tau_2)+\cdots+(1-\tau_\text{N}) \geq N\sqrt[N]{\prod_{i=1}^{\text{N}}(1-\tau_\text{i})}. \qquad (16)$$

Hence,

$$\begin{aligned} \left(\frac{N-\sum_{\text{i}=1}^{\text{N}}\tau_\text{i}}{N}\right)^{\text{N}} &\geq \prod_{\text{i}=1}^{\text{N}}(1-\tau_\text{i}),\\ \left(1-\frac{\tau_{\text{total}}}{N}\right)^{\text{N}} &\geq \prod_{\text{i}=1}^{\text{N}}(1-\tau_i). \end{aligned}$$

Finally, the idle probability of scheme 1 is higher than that of scheme 2.

$$(1-\tau_{\text{opti}})^N \geq \prod_{\text{i}=1}^{\text{N}}(1-\tau_\text{i}). \qquad (17)$$

Similar to the idle probability, the successful probability is proven as follows.

$$P_{\text{suc}} = \sum_{\text{i}=1}^{\text{N}}\tau_\text{i}\prod_{\text{j}\neq\text{i}}^{\text{N}}(1-\tau_\text{j}) \geq N\sqrt[N]{\prod_{\text{i}=1}^{\text{N}}\tau_\text{i}\prod_{\text{i}=1}^{\text{N}}(1-\tau_\text{i})^{\text{N}-1}}. \qquad (18)$$

This means that the P_{suc} reaches the minimum when the terms $\tau_\text{i}\prod_{\text{j}\neq\text{i}}^{\text{N}}(1-\tau_\text{j}),\ i=1,\cdots,N$ are equal. For each pair k,l, this becomes

$$\tau_k\prod_{\text{j}\neq\text{k}}^{\text{N}}(1-\tau_\text{j}) = \tau_\text{l}\prod_{\text{j}\neq\text{l}}^{\text{N}}(1-\tau_\text{j}), \qquad (19)$$

and then $\tau_\text{k}(1-\tau_\text{l}) = \tau_\text{l}(1-\tau_\text{k})$. As a result, $\tau_\text{k} = \tau_\text{l} = \tau_{\text{opti}}$ for all $k \neq l$. In this case, the minimum of P_{suc} can be rewritten as

$$\begin{aligned} P_{\text{suc}} &\geq N\sqrt[N]{(\tau_{\text{opti}}(1-\tau_{\text{opti}})^{\text{N}-1})^{\text{N}}},\\ &\geq N\tau_{\text{opti}}(1-\tau_{\text{opti}})^{\text{N}-1}. \end{aligned}$$

Compared to (6), the successful probability of scheme 2 is higher than that of scheme 1. However, the idle probability of scheme 2 is lower than that of scheme 1. In order to compare the throughputs of schemes 1 and 2, We analyze the function f. Using (17), we have

$$\begin{aligned} f &= \frac{\prod_{\text{i}=1}^{\text{N}}(1-\tau_i)(T_\text{s}-T)+T}{\sum_{\text{i}=1}^{\text{N}}\tau_i\prod_{\text{j}\neq\text{i}}(1-\tau_\text{j})}, \qquad (20)\\ &\leq g = \frac{\prod_{\text{i}=1}^{\text{N}}(1-\tau_\text{i})(T_\text{s}-T)+T}{N\tau_{\text{opti}}(1-\tau_{\text{opti}})^{\text{N}-1}}. \end{aligned}$$

The partial differential equation with respect to τ_i, $i = 1,\cdots,N$ is described as

$$\frac{\partial g}{\partial\tau_\text{i}} = \frac{(T_\text{s}-T)}{N\tau_{\text{opti}}(1-\tau_{opti})^{\text{N}-1}}\left(\prod_{\text{j}\neq\text{i}}(1-\tau_j) - \sum_{\text{l}=1}^{\text{N}-1}\prod(1-\tau_\text{j})\right). \qquad (21)$$

Because the function g reaches a maximum when $\frac{\partial g}{\partial\tau_\text{i}} = 0$, from $\frac{\partial g}{\partial\tau_\text{i}} = \frac{\partial g}{\partial\tau_\text{j}} = 0$ we have

$$\frac{\partial g}{\partial\tau_\text{i}} - \frac{\partial g}{\partial\tau_\text{j}} = 2\frac{(T_\text{s}-T)}{N\tau_{opti}(1-\tau_{\text{opti}})^{\text{N}-1}}\prod^{\text{l}\neq\text{i,j}}(1-\tau_\text{j})(\tau_\text{i}-\tau_\text{j}). \qquad (22)$$

Thus the function g and the function f reach a maximum when $\tau_\text{i} = \tau_\text{j}$ and this condition satisfies (17). As a result, the throughput becomes a minimum when the access probability of all sensors is equal. This means that the throughput of scheme 2 is higher than that of scheme 1.
In scheme 2, let us assume that the $\tau_\text{i} = i\frac{2\tau_{\text{total}}}{N(N+1)}$, and then the throughput of scheme 2 is higher than that of scheme 1. However when the number of sensors varies, the throughput of scheme 2 decreases or increases depending on the number of sensors in each system.
Moreover, because $T_\text{s} < T$, we have

$$(\tau_\text{i}-\tau_\text{j})\left(\frac{\partial g}{\partial\tau_\text{i}} - \frac{\partial g}{\partial\tau_\text{j}}\right) = \qquad (23)$$

$$2\frac{(T_\text{s}-T)}{N\tau_{\text{opti}}(1-\tau_{\text{opti}})^{\text{N}-1}}\prod^{\text{l}\neq\text{i,j}}(1-\tau_\text{j})(\tau_\text{i}-\tau_\text{j})^2 \leq 0. \qquad (24)$$

Consequently, the function g is Schur-concave [9]. Note that when the function g decreases, the function f also decreases and the throughput increases. This means that the system throughput is Schur-convex.

IV. MULTIPLE-HOP TOPOLOGY FOR WBANS

A. System model for multiple-hop topology

The system model for the multiple-hop topology is the same as that for the one-hop star topology which is described in

Sec. II-A. However, in the multiple-hop system, the sensor can transmit the signal to its neighbor sensor instead of the coordinator. The sensor that transfers the signals of neighbor sensors is called a relay sensor, and the sensor that transmits its signal to the neighbor sensor or the coordinator is called the transmit sensor. Because all sensors generate packets of vital data for transmission to the coordinator, all of the sensors are transmit sensors, and they can all act as relay sensors for the other sensors. For each path (from a transmit sensor to the coordinator), the transmit power of the transmit sensor and relay sensors on a given path is expected to be lower than that in the one-hop topology (direct path). However, the total transmit power of all sensors in a given path may be higher than that of a direct path. Thus, we assume that the signal is transmitted to the coordinator via multiple-hop only in cases where the total transmit power of all sensors on this path is equal to or lower than the transmit power of the direct path.
We assume that the access probability (τ) of all sensors in the multiple-hop system is the same as that of the one-hop topology. However, in the multiple-hop system, relay sensors should transfer the signal of the other sensors; hence, the access probability of relay sensors increases according to the number of paths to which it joins. As a result, in the multiple-hop system, we should consider a different access probability.

B. Mechanism for calculating throughput

The mechanism for the routing and calculating the throughput are described as follows.

1) Routing: After receiving a packet requesting a connection from a transmit sensor, the relay sensor estimates the channel model according to the received transmit power, and calculates the required transmit power for the transmit sensor according to $dSNR_{\text{thres}}$. The relay sensor adds the estimated transmit power of the transmit relay, renews the number of hops in the packet, and broadcasts the packet to all neighboring relays using the maximum transmit power. The neighboring relay that receives the packet destroys it if the number of hops in the packet is higher than the maximum number of hops; otherwise, the neighboring relay estimates the transmit power of the relay sensor, adds it to the packet, renews the number of hops, and broadcasts the packet using maximum transmit power. The process is then repeated until the packet arrives at the coordinator. After receiving the packet requesting a connection, including direct packets, the coordinator calculates the total transmit power for each path and replies to the transmit sensor via the path that has the minimal total transmit power. If none of the multiple-hop paths require a total transmit power that is less than or equal to that of the direct path, the coordinator replies directly to the transmit sensor. In the reply packet, the relay sensor (if necessary) and its transmit power are both specified.

2) Transmit power of sensors: As mentioned above, relay sensors and their corresponding transmit powers are specified in the reply packet that is sent to each transmit sensor; hence, if a sensor joins multiple paths, there may be different transmit powers. In this case, the transmit power is the maximum one.

3) System throughput: The sensor that directly transmits or transfers data packets to the coordinator is called the final sensor. Thus, the throughput is the total throughput of all paths that exist between the final sensors and the coordinator.
The simulation result is described in the following section.

V. NUMERICAL EVALUATION FOR MULTIPLE-HOP TOPOLOGY

A. System parameter

We assume that N sensors are randomly distributed on the body. All of the sensors can control their own transmit powers, and can communicate with sensors that are within their transmit range. In this paper, because we assumed that the relay sensor can receive error-free data when the received SNR is greater than or equal to $dSNR_{\text{thres}}$, we did not include a detailed analysis of their modulation and coding. The relation between $dSNR_{\text{thres}}$ and $eSNR_{\text{thres}}$ becomes important. The value of $dSNR_{\text{thres}}$ is assumed to be fixed at 0 dB, while $eSNR_{\text{thres}}$ is varied, e.g. -5 dB, -10 dB, and -15 dB. When sensor i transmits a signal to other sensors, if the received SNR of sensor j is greater than or equal to that of $eSNR_{\text{thres}}$, sensor i is called the effective sensor of sensor j, and sensor i is said to be within the effective range of sensor j. In addition, if the received SNR of sensor j is greater than or equal to that of $dSNR_{\text{thres}}$, sensor i is said to be within the transmit range of sensor j. The maximum number of hops changes, e.g. 1, 2, 3, and 4. In this paper, the channel model is defined as the one of body surface to body surface, CM3 [8]. The path amplitude δ is modeled by an exponential decaying factor ζ with Rician factor ξ in dB as follows.

$$10log_{10}|\delta|^2 = \xi + 10log_{10}\left(exp(\frac{-\iota_{\text{d}}}{\zeta})\right) + \beta, \quad \text{for d} \neq 0, \quad (25)$$

where β is a stochastic term having the log-normal distribution with zero-mean and standard deviation σ, ι_{d} is the propagation delay, which depends only on the distance between the sensors or between sensors and the coordinator, d. An example of a channel model is set as $\xi = 8, \zeta = 3, \sigma = 1$ and the numerical result is described in the following sections.

B. Throughput

Fig. 2 shows the throughput when the $eSNR_{\text{thres}}$ and the number of sensors are changed. As shown in Fig. 2, in the multiple-hop system, as the number of hops increases, so too does the possible system throughput that can be achieved. This can be explained from Figs. 3 and 4. When the number of hops increases, the transmit power of each sensor is decreased. Therefore, there are a smaller number of effective sensors. Moreover, the number of paths between the final sensors and the coordinator decreases, which means that the total access probability of each path is high. The total number of paths in a system is the same as the number of sensors. However, in the case of a single hop, the access probability of each path is the same, while in the case of multiple hops, as the number of hops increases, there is a larger number of paths whose access probability is zero. On the other hand, the access probability of

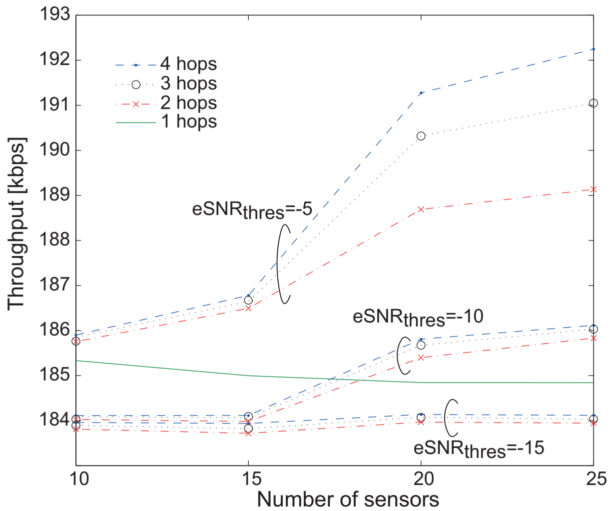

Fig. 2. Throughput with different values of $eSNR_{\text{thres}}$

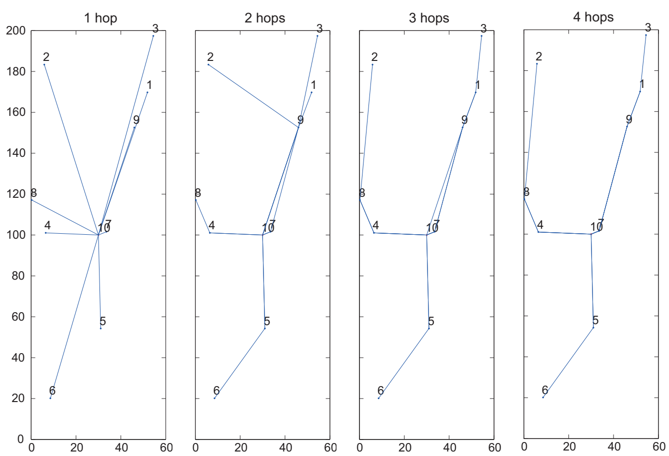

Fig. 3. Paths from the transmit sensors to the coordinator, N=10

the other paths increases. Consequently, for a higher number of hops, the access probability of all paths is determined by the access probability of all paths when there are a smaller number of hops. According to lemma 2, the throughput is Schur-convex, and the throughput of the larger number of hops is therefore higher. On the other hand, compared to one hop systems, when $eSNR_{\text{thres}}$ is significantly less than $dSNR_{\text{thres}}$, the throughput of the one-hop star topology system is higher than that of multiple-hop systems. The reason for this is that lemma 2 can also be applied to the case with a lower $eSNR_{\text{thres}}$, however, the overall number of effective sensors and the coordinator significantly increases. Therefore, the total access probability of the final sensors becomes substantially lower than τ_{total} , and the throughput of one hop is higher than that of multiple hops. On the other

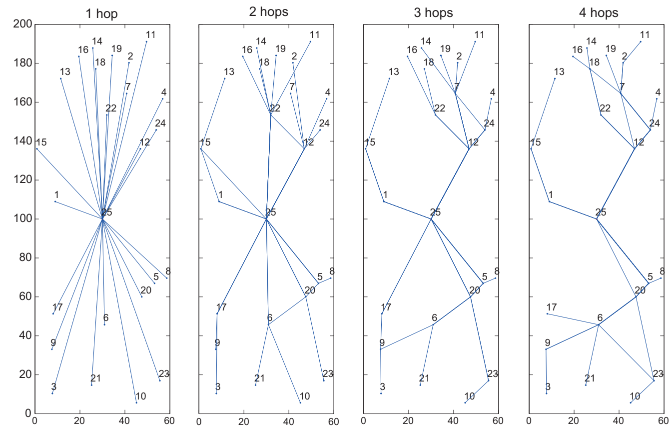

Fig. 4. Paths from the transmit sensors to the coordinator, N=25

hand, when $eSNR_{\text{thres}}$ is close to $dSNR_{\text{thres}}$,the throughput increases as the number of hops increases. The reason for this is as explained above.

C. Transmit power

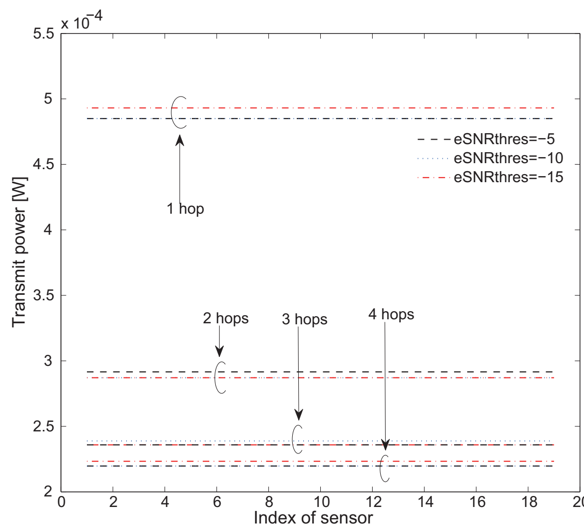

Fig. 5. The average transmit power of each sensor in case N=15

Fig. 5 shows the average transmit power of each sensor after 10,000 simulations. For the same number of hops, the transmit powers of all sensors are the same even when $eSNR_{\text{thres}}$ is changed. However, the transmit power decreases when the number of hops increases. This is an advantage of multiple-hop systems, not only in the context of WBANs, but also with general wireless multiple-hop systems. In order to evaluate the fairness of all sensors, we consider the variance of the transmit power.

$$Var = \sum_{\mathrm{i}=1}^{\mathrm{N}} (p_{\mathrm{i}} - \bar{p})^2, \tag{26}$$

where p_i and $\bar{p}$ denote the transmit power of sensor i and the average transmit power of all sensors, respectively. Fig. 6

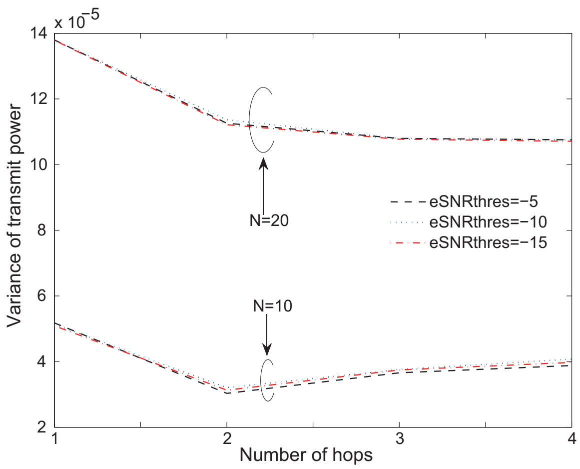

Fig. 6. The variance of transmit power

shows the variance of the transmit power in the case where the number of sensors is changed, e.g., 10 and 20. Note that in the one-hop topology, the transmit power depends on the distance between the sensors and the coordinator. In addition, some sensors are far from and some sensors are close to the coordinator. Therefore, the variance of the transmit power in one-hop systems is highest, regardless of the number of sensors. In the case where the number of sensors is small, as the number of hops increases, so too will the variance of the transmit power. This can be explained as follows. In the case where the number of hops is large, only a few sensors function as relay nodes. The transmit power of relay nodes is higher than that of the other nodes. In particular, when the number of sensors is small, the relay sensors are not always close to the coordinator (Fig. 3). Therefore, the transmit power of relay sensors is much higher than that of transmit sensors. On the contrary, in the case where the number of hops is low, many sensors function as relay sensors, and the difference in the transmit powers of the transmit sensors and relay sensors is therefore not very high. As a result, although the average transmit power of all sensors is lower when there is a larger number of hops, the variance of the transmit power is higher than in the case where there is a lower number of hops.

On the other hand, in the case where the number of sensors is high, the sensors that are close to the coordinator function as the relay node, and the transmit power of the relay sensors is therefore not significantly higher than that of the other nodes. Consequently, as the number of hops increases, the variance of the transmit power decreases.

VI. CONCLUSION

In this paper, we analyzed the performance of a multiple-hop WBAN system with the CSMA/CA protocol based on IEEE 802.15.6. We obtained the optimal access probability with respect to the throughput for a one-hop topology, and we proved two lemmas to discuss the performance of multiple-hop systems. We proposed an algorithm to calculate the throughput, and we analyzed both the throughput and the transmit power of the system. Generally, as the number of hops increases, the potential system throughput also increases. However, the system throughput decreases when the threshold of the effective SNR is much lower than the threshold of the desired SNR. On the other hand, as the number of hops increases, the average transmit power decreases. However, when the number of sensors is small, there is a larger number of hops, and there is a higher transmit power variance, whereas when the number of sensors is large, as the number of hops increases, the variance of the transmit power will decrease.

We proposed a performance analysis method for systems that are based on the IEEE 802.15.6 standard. However, this method can also be used to analyze the system performance for systems that are based on other standards, such as IEEE 802.15.4 and IEEE 802.11, by changing the parameters according to these standards. In future work, we will compare the system performance for different standards. Furthermore, we assumed that the modulation and coding followed the IEEE 802.15.6 standard, and did not consider the delay. This will also be included in future work.

REFERENCES

[1] Wireless Personal Area Network Working Group, "IEEE Standard 802.15.6, Wireless Body Area Networks," IEEE standards, pp. 1-271, 2012.

[2] Jovanov, E., Milenkovic, A., Otto, C., and de Groen, P., A "Wireless Body Area Network of Intelligent Motion Sensors for Computer Assisted Physical Rehabilitation," JNER 2(6):16-23, 2005.

[3] Marinkovi, S. J., Popovici, E. M., Spagnol, C., Faul, S., and Marnane, W. P., "Energy-efficient Low Duty Cycle MAC Protocol for Wireless Body Area Networks," IEEE Transactions on Information Technology in Biomedicine, 13(6):915-925, 2009.

[4] Eun-Sun Jung, Nitin H. Vaidya "A Power Control MAC Protocol for Ad Hoc Networks," MOBICOM-02, September, pp. 23-28, Atlanta, Georgia, USA, 2002

[5] Akkaya, K. and Younis, M., "A Survey on Routing Protocols for Wireless Sensor Networks," Ad Hoc Networks 3(3): pp. 325-349, 2005.

[6] IEEE 802.15.4/D01, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs) used in or around a body," 2010.

[7] Giuseppe B., "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," IEEE Journal on Selected Areas in Communications, Vol. 18 , Issue 3, March 2000.

[8] Harri, V., Matti, H., Jari, I., Attaphongse, T., "Different Experimental WBAN Channel Models and IEEE 802.15.6 Models: Comparison and Effects," 2nd International Symposium on Applied Sciences in Biomedical and Communication Technologies, ISABEL, Nov. 2009

[9] Ionel, R., "A Note on Schur-concave Functions" Springer, Journal of Inequalities and Applications, doi:10.1186/1029-242X-2012-159, 2012.