A Hexagon Tessellation Approach for the Transmission Energy Efficiency in Underwater Wireless Sensor Networks

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and Seonyeong Park*

Abstract—The energy efficiency is a key design issue to improve the lifetime of the underwater sensor networks (UWSN) consisting of sensor nodes equipped with a small battery of limited energy resource. In this paper, we apply a hexagon tessellation with an ideal cell size to deploy the underwater sensor nodes for two-dimensional UWSN. Upon this setting, we propose an enhanced hybrid transmission method that forwards data packets in a mixed transmission way based on location dependent direct transmitting or uniform multi-hop forwarding. In order to select direct transmitting or uniform multi-hop forwarding, the proposed method applies the threshold annulus that is defined as the distance between the cluster head node and the base station (BS). Our simulation results show that the proposed method enhances the energy efficiency compared with the existing multi-hop forwarding methods and hybrid transmission methods

Keywords—UWSN, Hexagon Tessellation, Energy Efficiency, Hybrid

1. Introduction

Recently, there has been a growing interest in monitoring the marine environment for scientific exploration, commercial exploitation and coastline protection. However, these tasks are not easy because its currents, chemical composition, and the ecosystems are all highly variable across space and time. The ideal method for this type of extensive monitoring is deploying with a networked underwater wireless sensor, referred to as the UWSN [1-3].

An UWSN consists of a variable number of sensors and vehicles that are deployed to perform a collaborative monitoring task over a given area and that are equipped with a small battery of limited energy resource.

In this paper, we investigate how the network's energy consumption is affected by the transceiver parameters and transmission method, and suggest a hybrid energy efficient transmission algorithm based on a hexagon tessellation approach. Our work is inspired by the previously proposed battery lifetime estimation and optimization for underwater sensor networks [1, 2]. We

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apply the proposed approach to the underwater sensor network model for two-dimensional UWSN.

The outline of the paper is as follows. In Section 2, we discuss the related works and proposed fundamentals. In Section 3, we propose a network model for the UWSN and a hybrid transmission method based on the concept of the threshold annulus that distinguishes the point of direct transmitting or uniform multi-hop forwarding. In Section 4, we describe the simulation results. Finally we conclude this paper in Section 5.

2. RELATED WORKS AND PROPOSED FUNDAMENTALS

2.1 Related Works

In underwater scenarios, lowering energy consumption and prolonging network lifetime are much more important since it is very difficult to replace or recharge the battery for the sensors [4, 5]. The transmission range is expected to contribute to these aims.

In general, the transmission energy consumption in the traditional single hop communications is excessive due to too long transmission range. On the other hand, the multi-hop communications decrease the transmission energy consumption by shortening transmission range; however, it may increase the receiving energy consumption like the case of the MTE(Minimum Transmission Energy) algorithm[6].

In terrestrial sensor networks, the routing algorithms proposed in [7], GAF(Geographical Adaptive Fidelity)[8], and GeRaf(Geographic Random Forwarding)[9] introduce the radio range. However the radio range only considers the physical characteristics of the sensors, which is not an optimum range for minimizing the energy consumption. Moreover the authors use the optimal shortest hop count routing scheme only suitable for ad hoc wireless networks.

In this paper, we focus on how the UWSN's energy consumption is affected by the under water transceiver parameters and transmission range and transmission method. Upon this analysis, we propose a solution to the requirements mentioned above, lowering energy consumption and prolonging network lifetime, for two-dimensional UWSN.

2.2 Two-dimensional Underwater Sensor Networks Modeling

The General architectures and the challenges for UWSNs have been addressed by many researchers[1, 10, 11]. There are two types of architectures: two-dimensional and three-dimensional UWSNs. In this paper, we focus on the two-dimensional architecture that has greater potential for covering wide areas of interest. Typical applications include environmental monitoring and the monitoring of underwater plates in tectonics.

One of the reference architectures for two-dimensional underwater network is shown in Figure 1. Here a group of sensor nodes are anchored to the bottom of the ocean with an ocean anchor. Their sensor nodes are interconnected to one or more underwater sinks(uw-sinks) by means of wireless acoustic links. An uw-sink is a network device in charge of relaying data from the ocean bottom network to a surface station [12]. An uw-sink performs the role of the base station (BS), in general, in wireless sensor networks. So we will consider each uw-sink as a BS.

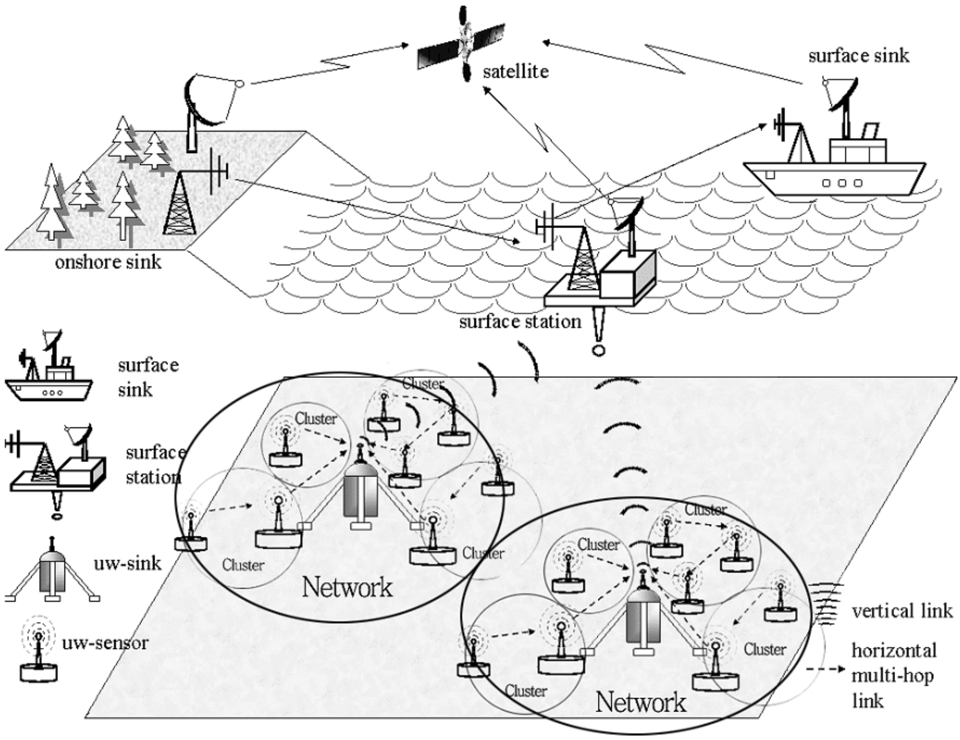

Fig. 1. Two-dimensional UWSN architecture Model

2.3 Underwater Acoustics Fundamentals

The realization of UWSNs requires a variety of techniques that have been developed for terrestrial sensor networks: wireless communication, low-power hardware, energy conserving network protocols, time synchronization and localization, programming abstractions and so on. However, some of the techniques are fundamentally irrelevant to underwater application. For example, radio is not generally suitable for underwater communication because of extremely limited propagation. Instead the acoustic signal is used for the majority of underwater wireless networks. Particularly, the energy consumption required for sensing and computation is several orders of magnitude lower than that of the communication energy consumption. These facts have led us to focus only on the acoustic communication energy consumption.

2.3.1 Passive Sonar Equation

It is well-known in the literature [13] that the signal to noise ratio (*SNR*) of an emitted underwater signal at the receiver is characterized by the following:

$$SNR = SL - TL - NL + DI \tag{1}$$

Where, *SL* is the source level, *TL* the transmission loss, *NL* the noise level, and *DI* the directivity index. All the quantities in equation (1) are in dB.

With omni-directional hydrophones in our model, the directivity index *DI* is 0. Considering the target *SNR* of 15 dB [13] at the receiver, the average ambient noise level *NL* is about 70 dB in most shallow waters. Then, we can express the source level *SL* intensity as a function of *TL* only as:

$$SL = TL + 85 \tag{2}$$

in dB.

2.3.2 Transmission Loss

Acoustic signal transmission in shallow waters can be approximately described by a cylindrical propagation model bounded by the water surface at the top and the sea floor at the bottom. Urick [13] provided the following equation to estimate the transmission loss in dB for a cylindrically spreading signal:

$$TL = 10\log d + ad \times 10^{-3} \tag{3}$$

Where, d is the distance between source and receiver in meters, α is the frequency dependent medium absorption coefficient.

Equation (3) describes that acoustic signal loses its energy as it travels through the underwater medium, mainly due to the distance dependent attenuation and the frequency dependent medium absorption. According to [14] the average medium absorption at temperatures between 4°C and 20°C is given by:

$$\alpha = \begin{cases} 0.0601 \times f^{0.8552} & 1 \le f \le 6 \\ 9.7888 \times f^{1.7885} \times 10^{-3} & 7 \le f \le 20 \\ 0.0601 \times f - 3.7933 & 20 \le f \le 35 \\ 0.0601 \times f - 11.2 & 35 \le f \le 50 \end{cases} \tag{4}$$

Where, f is in the frequency *kHz*, and α is in dB/km [9].

Using equation (4), we can calculate medium absorption for a wide frequency range of interest.

2.3.3 Transmission Energy

We have shown how the source level *SL* is related to inter-node distance d and frequency f through the equations (2), (3) and (4). *SL* is also related to the signal intensity I at one meter from the source according to the following expression:

$$SL = 10\ log\ \frac{I}{1\mu\text{Pa}} \tag{5}$$

Where, I is in μPa. Solving for I yields:

$$I = 10^{SL/10} \times 0.67 \times 10^{-18} \qquad [\text{Watts}/\ m^2] \tag{6}$$

Where, the constant converts μPa into Watts/m^2.

On the other hand, the transmitter energy, e, needed to achieve the intensity I in the direction of the receiver can be expressed as:

$$e = 2\pi \times 1m \times H \times I \qquad [\text{Watts}] \tag{7}$$

Where, H is the water depth in m [13].

In summary, we have presented a method to obtain the required transmitter power for signal transmission at the given distance d and frequency f between underwater sensor nodes. For this, we first calculate the transmission loss TL in terms of f and d and subsequently compute the source level SL that yields the source intensity I. Finally, we can obtain the corresponding transmitter power needed to achieve the desired intensity of I.

2.4 Hexagonal Tessellation Modeling

The realization of UWSNs requires a variety of techniques that have been developed for terrestrial sensor networks: wireless communication, low-power hardware, energy conserving network protocols, time synchronization and localization, programming abstractions and so on. However, some of the techniques are fundamentally irrelevant to underwater application. For example, radio is not generally suitable for underwater communication because of extremely limited propagation. Instead the acoustic signal is used for the majority of underwater wireless networks. Particularly, the energy consumption required for sensing and computation is several orders of magnitude lower than that of the communication energy consumption. These facts have led us to focus only on the acoustic communication energy consumption.

Figure 1 shows a network topology with several clusters. Each cluster has an uw-sink that works as a BS in this paper. Here, we apply a hexagon tessellation scheme to cover the surface of the cluster as shown in Figure 2. The BS is located at the center and each cell contains several sensor nodes. Now we define the center annulus A_1 a set of cells that are adjacent to and surrounding the center cell, and use A_k to represent the set of cells surrounding A_{k-1}.

A node is randomly chosen from each cell as the cell head. Only the cluster head node in each cell will receive and forward its own packets and packets from the outer annuluses. The other nodes in the cell can sleep most of the time and wake up only to sense the event or transmit their own packets. To balance the energy consumption among nodes in each cell, the cluster head node is reelected periodically [15].

We observe that annuluses hold the following properties:

- The number of cells in annulus, A_k, is $6k$, $k = 1, 2\ldots$
- The total number of annuluses, q, needed to fully cover the disk of radius of R, satisfies:

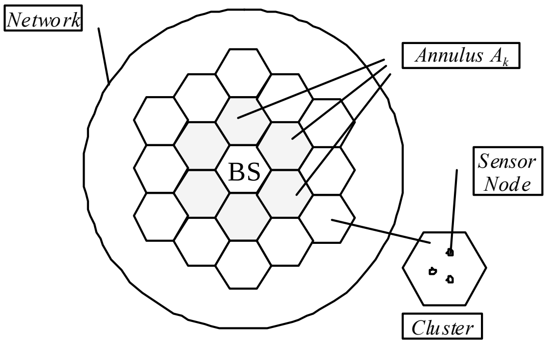

Fig. 2. Hexagonal tessellation of a cluster given in Fig.1

$$\begin{cases} \frac{(3q+1)l}{2} = R & \text{if } q \text{ is odd} \\ \frac{l\sqrt{(3q+1)^2+3}}{2} = R & \text{if } q \text{ is even} \end{cases} \tag{8}$$

In this model, the communication between a cluster head node and the BS is established through either multiple small hops via intermediary cluster head nodes or a single hop direct connection. For these, two types of transmission ranges are defined: uniform forwarding or direct transmission.

2.4.1 Uniform Forwarding Range

For sensor networks using the multi-hop forwarding approach, the uniform forwarding range between two nodes in adjacent cells is as shown in Figure 3.

In order to guarantee that any two cluster head nodes in adjacent cells can reach each other, we require the forwarding range to satisfy:

$$r_f \geq \sqrt{13}l \tag{9}$$

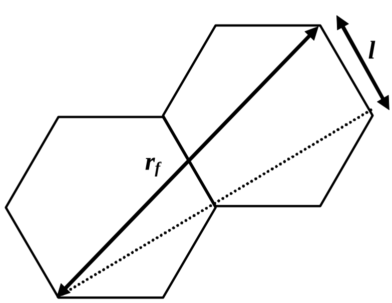

Fig. 3. Minimum range of uniform multi-hop forwarding

2.4.2 Direct Transmission Range

In addition to forwarding packets via multiple intermediate hops, each node can also transmit them directly to the BS. Because of the concentric layouts of hexagonal cells, every cluster head node in annulus A_k uses the same direct transmission range r_k given by:

$$r_k \geq l\sqrt{3(k+1)^2+1}, \qquad k = 1, 2 \cdots. \tag{10}$$

We observe that the direct transmission range for each node depends on the distance between the corresponding cluster head node and its BS.

2.5 Issues in Designing UWSN

2.5.1 Importance of Ideal Cell Size

One of the most important considerations in designing a sensor network is the limited battery resources in each sensor node, largely due to the difficulty and cost of recharging sensor batteries once the network is deployed. In proposed network model, the inter-node distance d has a significant impact on energy consumption. Since d is dependant on the cell size, the optimal decision on the ideal cell size is crucial for the longevity of the entire UWSN. This will be discussed in detail in Section 3.1.

2.5.2 Energy Efficiency in Hexagon Modeling

In the multi-hop hexagon model, cluster head nodes closer to the BS forward the data from nodes farther from the BS. Distant cluster head nodes spend energy to send the data to the next hop. But closer cluster head nodes need more energy to relay the data in addition to their own.

If the energy consumption is based solely on the distance, then the cluster head nodes closest to the BS must forward the data of all the other nodes in the network.

In this case, however, the nearest cluster head nodes will be overloaded and will be the first to run out of battery. Thus the network will not be able to work any more. Therefore, it is particularly important that the energy cost for data forwarding does not overburden the nearest cluster head nodes to the BS.

We propose a hybrid forwarding method to solve this problem in the next section.

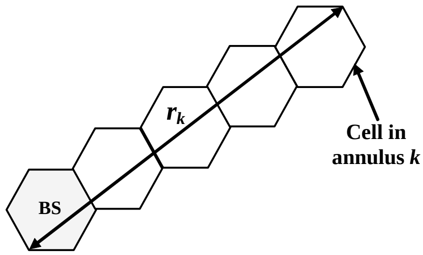

Fig. 4. Maximum range of uniform multi-hop forwarding

3. NETWORK MODELING WITH EFFICIENT HYBRID TRANSMISSION

3.1 Ideal Cell Size

In hexagon model, the number of cluster head nodes in Annulus A_k is given by:

$$n_k = 6k \times \frac{3\sqrt{3}}{2} nl^2 /(\pi R^2) = \frac{9\sqrt{3}knl^2}{\pi R^2} \tag{11}$$

Then the following is given for the total energy consumption of all of the cluster head nodes which transmit packets from outer annuluses as well as its own packets in A_k:

$$E_k = \frac{e_t(r_f)\sum_{i=k}^{q} 9\sqrt{3}inl^2 + e_r \sum_{i=k+1}^{q} 9\sqrt{3}inl^2}{\pi R^2} \tag{12}$$

The average energy consumption per cluster head node in A_k is given by:

$$e_k = \frac{E_k}{n_k} = \frac{e_t(r_f)\frac{q+k}{2}(q-k+1) + e_r \frac{q+k+1}{2}(q-k)}{k} \tag{13}$$

From equation (7), we can obtain the required energy, e, for data transmission at the uniform forwarding range: $r_f = \sqrt{13}l$ and the frequency f = 10 kHz. The receive energy, e_r, is typically set around one fifth of the transmit energy in commercially available hydrophones [16].

The cluster head nodes of the innermost annulus A_1 are the most heavily loaded by forwarding almost all the packets in the network to the BS. It is estimated as:

$$e_{\max} = e_1 = (e_t + e_r)\frac{q(q+1)}{2} - e_r \tag{14}$$

According to equation (14), we can obtain a relationship between e_{max} and the cell size l in the UWSN. Here, we may also consider the number of nodes together. And due to the imbalanced in energy consumption caused by asymmetric traffic forwarding toward the BS, the optimal cell size for total network energy consumption does not lead to the maximum network lifetime in stationary networks.

In order to fully cover the given disk area, we calculate optimal cell size, l, by adapting equation (8). The relationship between the number of annuluses q and cell size l is shown in Figure 5.

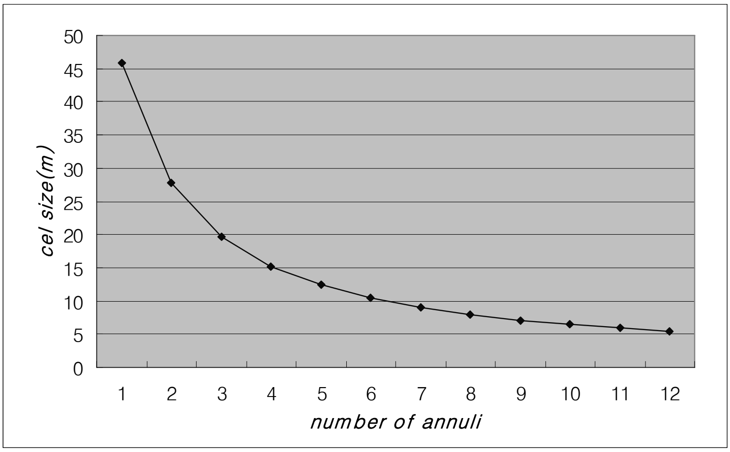

Fig. 5. Relationship between annuluses q and cell size l (R=100m)

3.2 Suggested Network Modeling for UWSN

Considering environmental monitoring or underwater tectonics plates applications monitoring, we have proposed two-dimensional underwater network architecture as shown in Figure *1*. We divide the given network area into several clusters, each with radius $R = 100m$. Then, we apply a hexagonal tessellation model to each network applying the description given in Section 2.3.

When the radius R is $100m$, by applying the relationship between annuluses and cell size given in Figure 5, the number of annulus q is 7 as shown in Figure 6 and we obtain that the ideal

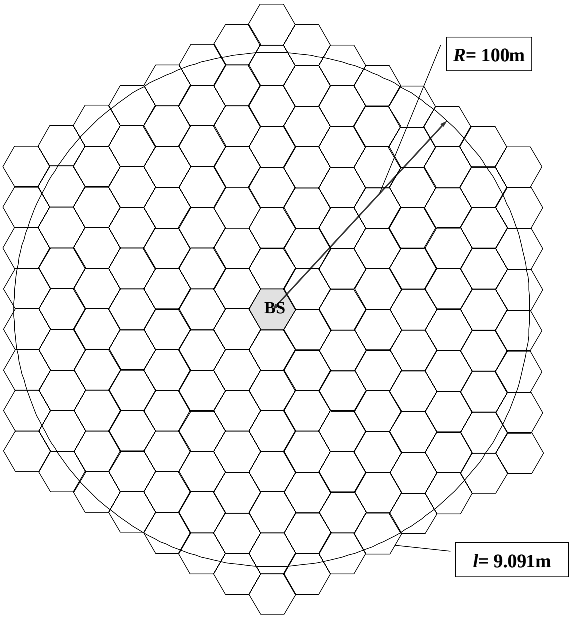

Fig. 6. Network model for UWSN

cell size l is 9.091m.

3.3 Enhanced Energy Efficient Hybrid Transmission Method

To achieve the balanced energy consumption in the given network, we propose a hybrid transmission method based on the location dependent direct transmission and the uniform multi-hop forwarding mixed. For simplicity, we assume that only one node is active in every cell during each round in our model.

As shown in Figure 7, the proposed hybrid transmission method can be summarized as follows.

- For cluster head nodes in annulus A_k, where $m < k \leq q$, use the multi-hop forwarding scheme;
- For cluster head nodes in Annulus A_k where $1 \leq k \leq m$, transmit the data directly to the BS;
- The value m is the threshold for choosing the forwarding schemes.

In the case of the existing uniform forwarding method, the total traffic is concentrated on the cluster head nodes in the annulus A_1. But with the proposed hybrid transmission method, the total energy consumption is shared among the cluster head nodes in annulus A_m. There being more cluster head nodes in A_m than A_1, e_{max}, is reduced proportionately while the lifetime is increased.

Note that in the uniform transmission method, applying equations (9) and (10), the total energy consumption of the annulus A_k is:

$$E_k = e_t(r_k)N_k^d + e_t(r_f)N_k^f + e_r N_{k+1}^f \tag{15}$$

Where, N_k^f represents the number of packets forwarded to A_{k-1}. Since all cluster head nodes are using the uniform forwarding scheme, the total traffic is concentrated on the cluster head

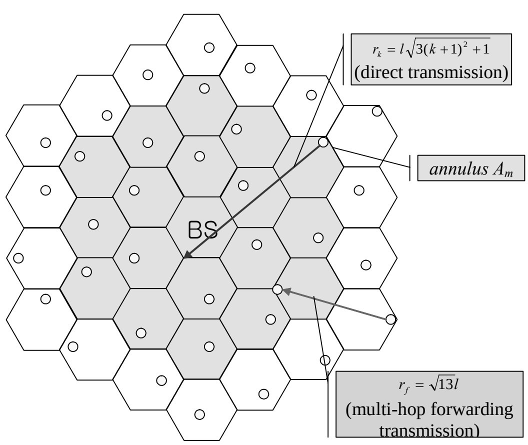

Fig. 7. Hybrid transmission method

nodes in the annulus A_1.

From equations (11) and (15), we obtain the average energy consumption per cluster head node in A_k:

$$e_k = E_k / n_k, \qquad k = 1, 2 \cdots. \tag{16}$$

In the proposed method, the cluster head nodes in the threshold annulus A_m directly transmit all the data to the BS. Therefore the total energy consumption at annulus A_k can be written as:

$$\begin{cases} k = q: & E_k = \sum [e_t(r_k) N_k^f] \\ m < k < q-1: & E_k = e_t(r_f) N_k^f + \sum_{i=1}^{q-k} [e_t(r_f) N_{k+i}^f] \\ & \quad + \sum_{i=1}^{q-k} [e_r(r_f) N_{k+i}^f] \\ k = m: & E_k = e_t(r_k) N_k^d + \sum_{i=1}^{q-m} [e_t(r_k) N_{k+i}^d] \\ & \quad + \sum_{i=1}^{q-m} [e_r(r_f) N_{k+i}^f] \\ \text{otherwise}: & E_k = \sum [e_t(r_k) N_k^d] \end{cases} \tag{17}$$

Where, N_k^f represents the number of packets forwarded to A_{k-1} and N_k^d the number of packets directly transmitted to the BS. Since the cluster head nodes in annuluses outside of A_m use the uniform forwarding scheme, the maximum energy consumption per cluster head node occurs in annulus A_1. With the hybrid transmission method, the total energy consumption is shared by the cluster head nodes in annulus A_m. The cluster head nodes in annuluses inside of A_m transmit only their data with increased power consumption to reach a greater distance to BS. Since the higher m, the more cells exist in A_m, the transmission load will be shared by more cells. In this way, e_{max}, can be reduced and the lifetime is prolonged.

Moreover, we can further enhance the hybrid transmission method by allocating the frequency adaptively. According to equations (3) and (4), the transmission loss is greater at higher frequencies, which implies that the nodes using high frequencies need to transmit acoustic signals at a higher energy in the underwater environment. Therefore, it is desirable to assign lower frequency bands to nodes in low annuluses and increasingly higher frequency bands to the outer annuluses according to the rule implied and discussed in Section 2.2. This assignment allows the nodes with a higher forwarding load to use the lower frequencies and thus save the energy.

4. Simulation and Performance Evaluation

We evaluate the performance of the proposed method via simulation studies. The network and transmission models of Section 2 and 3 are used for our experiments. We assume every cell has equal probability of signal detection. Since every cell covers an equal size of area, each cell generates the same amount of data packets.

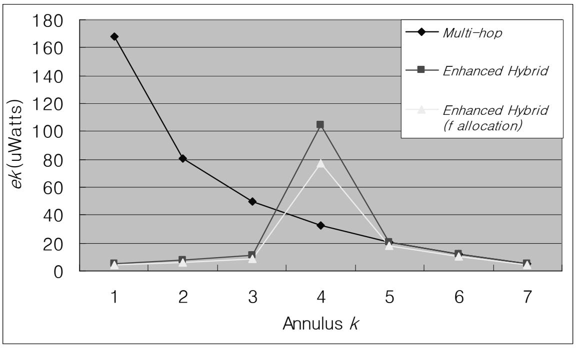

Fig. 8. Per cluster head node energy consumption over a range of annuluses*(R = 100m, l = 9.091m, H = 100m)*

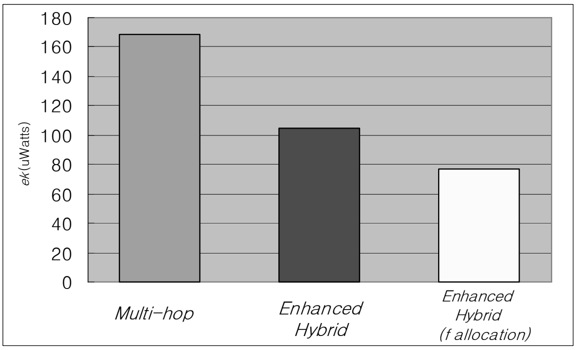

Fig. 9. Comparison of the maximum energy consumption cell *(R = 100m, l = 9.091m, H = 100m)*

We compare the proposed enhanced hybrid transmission method (*f* allocation) to the multi-hop forwarding method with the threshold $m = 4$. In these tests, the threshold annulus A_m is allocated the lowest frequency, and others are allocated a frequency of 50 kHz. According to the simulation results, the enhanced hybrid transmission method needs lower energy consumption than the multi-hop transmission method as demonstrated in Figure 8 and 9. The enhanced hybrid transmission method reduced approximately 37.65 % of the energy consumption for e_{max}. And there was a further reduction of 54.41 % with different frequency allocation.

5. Conclusion

This paper proposes an enhanced hybrid transmission based on the threshold annuluses for choosing the forwarding schemes. By using the hybrid transmission method, the total network traffic load can be shared by a greater number of nodes in the annulus A_m , thus alleviating the substantial overload at the innermost annulus of the multi-hop forwarding method.

According to the simulation results, the enhanced hybrid transmission method could reduce the energy consumption of the central annulus leading to an increased lifetime of the entire UWSN. Moreover, the network traffic load can be reduced further by allocating different frequencies to different annuluses.

This result means that the proposed hybrid transmission method is more energy efficient than the multi-hop forwarding method and the existing hybrid transmission method. Moreover our approach is more suitable for two-dimensional UWSN applications.

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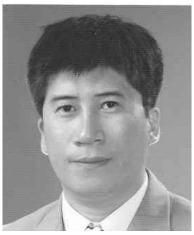

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