Received March 7, 2019, accepted March 22, 2019, date of publication March 27, 2019, date of current version April 13, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2907693

Energy Consumption in Relay Underwater Acoustic Sensor Networks for NDN

GUANGLIN XING[1], YUMENG CHEN[1], LIUTING HE[1], WANYAN SU[1], RUI HOU[1], (Member, IEEE), WEI LI[1], CHENGJUN ZHANG[2], AND XIQU CHEN[3]

[1]College of Computer Science, South-Central University for Nationalities, Wuhan 430074, China
[2]College of Mechanical Engineering and Automation, Wuhan Textile University, Wuhan 430070, China
[3]School of Electrical and Electronic Engineering, Wuhan Polytechnic University, Wuhan 430023, China

Corresponding author: Rui Hou (hourui@mail.scuec.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 60841001, Grant 61503418, and Grant 51875414, in part by the Natural Science Foundation of Hubei Province, China, under Grant 2017CFB585, in part by the Scientific and Technological Projects of Wuhan, China, under Grant 2015010101010008, in part by the Foundation of China Scholarship Council, and in part by the Special Fund for Basic Scientific Research of Central Colleges, South-Central University for Nationalities, under Grant CZT19011.

ABSTRACT In recent years, a typical representation of the next-generation Internet architecture, named data networking (NDN), and a critical form of the underwater Internet of Things (IoT), underwater acoustic sensor networks (UASNs), have attracted widespread attention in academia. Meanwhile, since the battery energy of the sensor node is limited and the battery is difficult to replace or recharge in underwater environments, extending the networks' lifetime has become a key issue in UASNs. In this paper, we try to deploy a UASN on NDN architecture and explore the energy consumption of the NDN-based UASN under shallow water and deep water conditions based on the relay network topology. A simulation is carried out to compare the delay performance of NDN-based and IP-based UASNs and validate the result. It is believed that the study could provide a theoretical criterion for the selection of the direct or relay path to optimize energy consumption in the future deployment of NDN-based UASNs.

INDEX TERMS Energy consumption, named data networking, underwater acoustic sensor networks.

I. INTRODUCTION

In recent years, the Internet of Things (IoT) technique has been widely applied to intelligent transportation, advanced manufacturing, intelligent cities, and more [1], and as the basic architecture of IoT, the wireless sensor network (WSN) has attracted the attention of the communication community, from hardware implementation to software protocol design. Underwater acoustic sensor networks (UASNs) are the form of underwater deployment of WSNs and are applied in marine data collection, military inspection, and disaster prevention, making them critical components of the current Internet [2]. Meanwhile, current IP-based internetworking architecture is moving from the host-based communication model to information-centric networking (ICN) model since the former is facing network address translation (NAT) and security issues, among others [3]. Therefore, future UASNs will use the information-centric data communication model as their message exchange approach. As one of the most promising implementations of ICN, named data networking (NDN) has been paid much attention by scholars around the world for its specific in-network caching and coupling routing characteristics, and it has been regarded as a typical representation of next-generation Internet architecture [4]. As mentioned above, in this paper, an NDN-based UASN has been proposed and its energy consumption has been studied based on a relay scenario to gain energy efficiency. To the best of our knowledge, there are very few related works on NDN-based UASNs, especially for energy research, thus we believe this study can provide theoretical and practical references for information-centric UASNs' deployment and optimization.

An NDN-based UASN is a self-organized network system that consists of a large number of micro-NDN nodes. These NDN nodes are randomly deployed within a certain geographical area and form an NDN network through self-organization. In NDN-based UASNs, each data information object has been designated with a unique name, such as "*/x/y/z/temperature*", in which x, y, and z denote the three-dimensional coordinates of an NDN node, respectively, and

The associate editor coordinating the review of this manuscript and approving it for publication was Mianxiong Dong.

temperature denotes the temperature of the node's location environment. Nodes can be mainly categorized as two types: the sink node and sensor nodes. The former receives messages sent by sensor nodes while the latter collects any information. The data communication process follows a Subscriber/Publisher model, in which any node that intends to obtain a specific data information object (Subscriber) creates an interest packet that contains the name of its desired data information object and sends it to other nodes; each node, after receiving the interest packet, searches its content storage (CS), records its name into the pending interest table (PIT), and forwards it from the forwarding interest table (FIB) until it finds the data information object's holder (Publisher). The Publisher creates a data packet containing the desired data information and sends it back to the Subscriber on the reversed path the interest packet has passed. In NDN-based UASNs, the sink node plays the role of Subscriber and the other sensor nodes play the role of Publisher in most cases.

There are many problems associated with deploying NDN-based UASNs, for example, those pertaining to communication range, battery power, cost, and caching in nodes. In NDN-based UASNs, the lifetime of a single sensor node is limited and it is inconvenient to recharge or replace the battery [5], [6]; thus, the lifetime of the sensor node depends, to a large extent, on the battery life, because unreasonable energy consumption could lead to the premature death of nodes. If any node stops communicating, the coverage area of the UASN is reduced, along with the network lifetime. Therefore, designing the NDN-based UASNs' routing for interest packets to reduce the energy consumption and improve the communication quality of the network is a key issue in the research field of UASNs.

In NDN-based UASNs, the power consumed for interest/data packet transmission and sending/receiving is the main energy consumption. Further, the power required for interest/data packet transmission is positively correlated to the distance between the source and destination nodes. The energy consumption can thus be reduced by reducing the distance between the Subscriber and Publisher node pairs, thereby extending the life cycle of the network. However, owing to the complexity and particularity of the underwater environment, sensor nodes are generally scattered randomly within a specified area, and are fixed only after initial deployment. This initial topology makes the distribution of nodes uneven, which may lead to network defects. Some nodes are so far apart that communication between them consumes a large amount of energy, and the communication might be invalid if the power is insufficient for transmission. In order to prolong the network lifetime and improve the communication efficiency, relay nodes must be set up between two nodes along the path of the Subscriber and Publisher to shorten the distance between two nodes and reduce the required power for communication between them to compensate for the geometric defects of the network topology.

The rest of this paper is organized as follows: in section 2, related works that refer to energy consumption optimization for WSNs, UASNs, and information-centric (IC)-based WSNs are described; then, an NDN-based relay UASNs data communication model is proposed for energy consumption optimization. An extensive simulation is conducted to verify the efficiency of the proposed model. Finally, we conclude the paper and present future research directions.

II. RELATED WORK

To the best of our knowledge, there are few works on energy consumption optimization for information-centric (IC) WSNs, especially for NDN-based relay UASNs. Li *et al.* [7]–[9] systematically studied the energy saving issue in WSNs, and realized 60 GHz data transportation for wireless industrial sensor networks. Xu *et al.* [10] proposed an energy saving approach for multi-tier heterogeneous networks. Xie *et al.* [11] established an energy-efficiency routing algorithm for obstacles that exist within WSNs. Long *et al.* [12] proposed a scheduling algorithm for the TDMA WSN system. Hahm *et al.* [13] proposed a cooperative caching approach for NDN-based IoT network architecture, which focuses on optimal data content scheduling for caching and sleeping nodes to gain low power consumption. Chen *et al.* [14] proposed an high-speed collaboration caching scheme for ICN-based WSNs, which focuses on the high-speed cache's capacity adjustment, data replacing frequency strategy, and data content replacement algorithm to optimal energy efficiency, target hit rate, and average delay. Song *et al.* [15], based on the concept of content-centric networking (CCN), proposed a resource constraining scheme that can assign tasks accords to devices' residence energy. Amadeo *et al.* [16] proposed an NDN-based optimal routing algorithm for WSNs that is triggered by the conventional routing strategy in datacenters. Xu *et al.* [17] proposed a dataset synchronization protocol with sleeping sensors scheme for NDN-based WSNs (DSSNs) to save energy. It uses an integrated interest/data packets approach and sleeping nodes to obtain energy efficiency. However, the schemes mentioned above do not consider relay-based packet routing optimization, and most importantly, the underwater environment is different to land-based WSNs.

In recent years, efforts to reduce the energy consumption of UASNs have mainly covered clustering routing [18]–[20], energy consumption balance [18], [21], and energy consumption optimization with different packet assembly methods [22], [23], among others. However, most studies have only considered the direct multi-hop linear topology, as shown in Fig.1(a), in which S_i and d denote the i-th underwater acoustic sensor node and distance between two adjacent nodes, respectively. In fact, the relay-based network topology shown in Fig.1(b) is a better fit for the requirements of UASNs. This topology has already been used in research on WSNs deployed on land [24]–[26]. However, it has not yet been applied in UASN studies, even IC-based UASNs. In practice, land WSNs use radio signals for communication whereas UASNs use acoustic signals, and hence, there is a significant difference in the energy consumption.

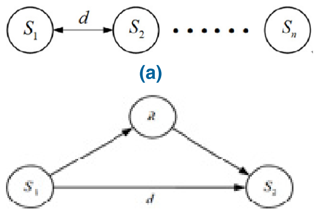


FIGURE 1. (a) Direct multi-hop linear topology. (b) Relay network topology.

In addition, research into the energy consumption of UASNs has not made the distinction between shallow water field and deep water field conditions. One study [27] analyzed the node energy consumption issue for shallow water fields and deep water fields, but it only referred to the multi-hop linear topology shown in Fig.1(a). Acoustic waves are attenuated when they are transmitted through the medium, and acoustic waves of different frequencies have different degrees of attenuation in different media. Thus, the energy consumption is also different due to the difference between deep and shallow water areas. However, only a handful of studies analyzed the differences in considerations between deep water and shallow water. Sehgal *et al.* [28] analyzed the energy consumption of underwater acoustic sensor networks in deep water and shallow water channels for different transmission mechanisms (single-hop, multi-hop, etc.), and although the results presented in this paper are quite useful, as mentioned above, it only refers to the multi-hop linear topology shown in Fig.1(a) and the distances between the nodes are fixed and equal. The difference in energy consumption at different sound frequencies is also not considered in this paper. Moreover, it only refers to conventional UASNs.

There exist several works focused on methods to select relays to achieve optimal performance in UASNs. Wang and Zhang [29] proposed an optimal relay selection scheme to minimize the energy consumption while guaranteeing the quality of service (QoS) of each link over MIMO-based underwater acoustic (UWA) wireless cooperative sensor networks. They formulated stochastic optimization for the relay selection as a restless multi-armed bandit system. Khan *et al.* [30] proposed an energy-based relay node selection protocol that divided three-dimensional UASNs into three areas, with the relay nodes selected in the middle layer. The selection of the optimal relay node was based on the relay's depth and location. The node corresponding to the highest value of location and depth was considered the optimal relay node. Ghafoor *et al.* [31] proposed an orthogonal frequency division multiplexing-based spectrum -aware routing (OSAR) relay selection protocol, which combined cognitive capability with a routing technique. It could determine a stable path between the source node and destination node by selecting the best relay node; the node with the minimum transmission delay was selected as the next relay node. Considering that the transmission power between nodes is mainly related to the amount of interest and data packets transmitted, in order to achieve high-quality data transmission some cooperative data transmission schemes for relays (e.g., [32]–[34]) have been proposed to alleviate the effect of energy limitations in UASNs. For example, in [32], the authors used an approach based on the multiuser multi-armed bandit (MU-MAB) framework for relay selection to reduce the amount of data exchanged. The authors in [33] considered the networking protocol and cooperative data transmission at the physical layer to enhance communication reliability in underwater acoustic sensor networks through an intermediate relay node. The relay node selection process considered the instant link conditions and distance cost successfully to forward packets to the destination node in the underwater environment. Liu *et al.* [34] considered the relay node layout and traffic distribution as a joint problem. They attempted to increase the network lifetime by iteratively moving the relay nodes to appropriate locations, and to optimize traffic between the nodes to balance the energy consumption to extend the life of a 3D underwater sensor network.

As mentioned above, ICN is considered as the future Internet architecture, thus it is the trend that WSNs are deployed on an ICN basis. Therefore, in this paper, we introduce a specific paradigm of WSNs, the UASN, to the NDN structure and research the energy consumption issue, which is based on the relay topology, considering both shallow water field and deep water field conditions. Moreover, the differences in energy consumption at different frequencies are analyzed. A simulation was used to validate the model and demonstrate that the model satisfies the selection rule between the direct path and the relay path for energy consumption optimization under shallow water field and deep water field conditions.

III. ANALYSIS OF ENERGY CONSUMPTION

In NDN-based UASNs, owing to the properties of acoustic wave propagation, the underwater channels depend on environmental factors such as ambient noise, pH, and temperature, which cause signal attenuation and energy loss. However, these factors involve great uncertainty and large local differences exist. This work primarily compares the energy consumption of relay and single-hop paths in deep and shallow water environments, and ignores the abovementioned factors. In underwater acoustic communications, the components consuming the maximum energy in the sensor nodes are the controllers and communication units, the former governing the processes of CS searching, PIT record and FIB forwarding, while the latter governs the process of interest/data packet assembly/disassembly and packet sending/receiving. The communication units are used for data transmission between nodes and have the largest energy consumption. Because 80% of the maximum energy consumption occurs in the transmission mode, transmitter power control has the potential to significantly influence the energy consumption. Unlike transmitter power, receiver power is independent of distance [5]. To simplify the model, this study only considers the energy consumption of sending and receiving packets by nodes.

Based on the acoustic sensor energy consumption model presented by Sozer *et al.* [6], the energy consumption to transmit a packet for a sending sensor node can be expressed as

$$E_{tx}(d) = P_{tx}T_{tx} = P_0 A(d) T_{tx}, \quad (1)$$

where P_{tx} is the transmission power, which is related to the distance between two adjacent nodes. To ensure that the receiving nodes can receive data reliably, the nodes can adjust the sending signal strength adaptively to optimize energy consumption. P_0 is the minimum receiving power level of nodes; $A(d)$ is the power attenuation coefficient as a function of distance d. T_{tx} is the time duration to transmit a packet for a node, and can be expressed as $T_{tx} = l/\lambda \cdot B(l)$, where l is the packet size in bits; $B(l)$ is the bit rate; and λ is the coding efficiency in bps/Hz.

In an underwater environment, the power attenuation parameter for an acoustic signal with fixed frequency is expressed as

$$A(d) = d^k c^d, \quad (2)$$

where k is the power factor reflecting the type of acoustic communication used in the model, with $k = 1$ and $k = 2$ denoting cylindrical and spherical propagation models, respectively. In addition, c is a power attenuation parameter related to signal frequency and can be expressed as

$$c = 10^{\partial(f)/10}, \quad (3)$$

where $\alpha(f)$ is the absorption coefficient in the underwater environment, and is the major factor limiting maximum bandwidth utilization, which can be expressed as [16]

$$\alpha(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \quad (4)$$

where f is the frequency (in kHz). Similarly, the energy consumption for a sensor node receiving a packet of length l can be expressed as

$$E_{rx} = P_{rx}T_{rx} \quad (5)$$

where P_{rx} is the receiver power; the energy is fixed to one that corresponds to the minimal signal power for the successful acceptance of a packet. T_{rx} is the packet's receiving time and can be expressed as $T_{rx} = l/\lambda \cdot B(l)$. In our energy consumption model of NDN-based UASNs, energy consumption includes the energy consumed for transmission and energy required for reception. The energy consumed by the transfer includes the energy consumed by the subscriber transferring the interest package to the publisher and the energy consumed by the data package from the publisher to the subscriber.

In this study, we assume that the sensor nodes of the UASN are static after deployment and are placed at the same water depth. The influence of the underwater environment on the bit error rate of the data transmission is ignored. Consider the two-hop relay scenario with source node S_1 (as a subscriber), destination node S_2(as a publisher), and relay node R, as shown in Fig.1(b). $S_1 - S_2$ is the single-hop direct path and $S_1 - R - S_2$ is the two-hop relay path. The distances of paths $S_1 - R$ and $R - S_2$ are d_1 and d_2, respectively; further, $d_1 = \theta_1 d$ and $d_2 = \theta_2 d$ where $0 < \theta_1 < 1$, $0 < \theta_2 < 1$, and $\theta_1 + \theta_2 \geq 1$.

In UASNs, the terms shallow water field and deep water field denote the conditions in which the sensor nodes are deployed in an underwater environment at depths of less than or more than 100m, respectively. Owing to the complexity of the underwater environment, the model of underwater acoustic propagation is different according to different depths. Under the shallow water condition, acoustic signals are transmitted within cylindrical channels with $k = 1$, whereas under the deep water condition, they are transmitted within spherical channels with $k = 2$. Then, the energy consumption for transmitting and receiving an interest packet and a data packet through the direct path $S_1 - S_2$ is

$$E_{direct} = 2 \cdot \left[E_{tx}\left(d^k\right) + E_{rx}\right]. \quad (6)$$

And the energy consumption for transmitting and receiving an interest packet and a data packet through the relay path $S_1 - R - S_2$ is

$$E_{relay} = 2 \cdot \left[E_{tx}\left(d_1^k\right) + E_{tx}\left(d_2^k\right) + 2E_{rx}\right]. \quad (7)$$

Therefore, we can use the difference between direct-path-based energy consumption and relay-path-based energy consumption to choose between the direct path and relay path for energy efficiency, as shown:

$$\Delta e = E_{direct} - E_{relay}. \quad (8)$$

IV. SIMULATION

To verify the results, the energy consumption models of NDN-based relay UASNs in shallow water and deep water are analyzed using NS-3, ndnSIM, and MATLAB. First, we compare the delay performance of NDN with IP networks. For simplicity but not loss the generality, in this simulation, we suppose all NDN-based UASN nodes are located in shallow water and use UDP Sockets for packets transmission in IP networks, and SHA-1 algorithm with a space size of 128 bits for both NDN and IP networks. All nodes are installed with the NDN and IP protocol stack. In the simulation, the sink node sends 1000 interest packets/query request packets into the NDN/IP-based UASN, and records the average delay when receiving data packets/feedback packets. We set the average size of interest packets/query request packets is 10 octets while the average size of data packets/feedback packets is 20 octets, and the sink node sends an interest packet/query request packet every 3 seconds. Fig.2 shows the average delay result of NDN- and IP-based UASNs. It can be seen that the NDN-based UASN's delay is roughly 50 ms for all cases while the IP-based UASN's delay increases obviously with the incrementing number of sensor nodes, thus indicating the

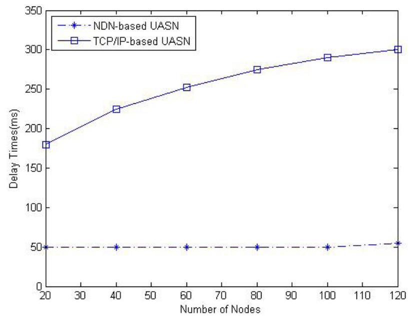


FIGURE 2. The average delay of NDN- and IP-based UASNs.

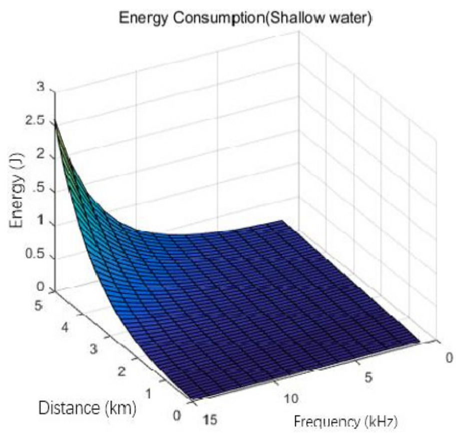


FIGURE 3. Relationship between energy consumption, node distance, and frequency for direct path in shallow water.

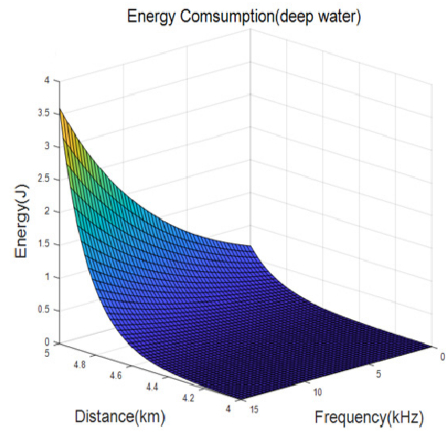


FIGURE 4. Relationship between energy consumption, node distance, and frequency for direct path in deep water.

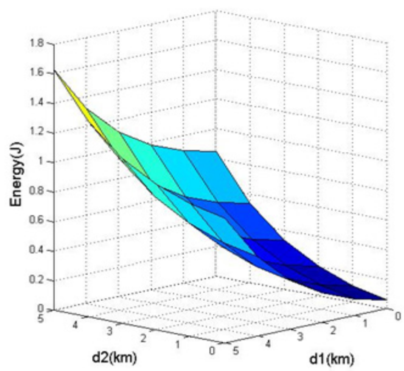


FIGURE 5. The Relationship between energy consumption and node distance for a relay path in shallow water with fixed frequency.

NDN-based network architecture has the more stable delay performance.

Furthermore, the energy consumptions in shallow water and deep water are analyzed. The parameters' value are $P_{rx} = 0.75W$ and $P_0 = 1W$, where a packet is transmitted with an average transmit time and receive time $T_{tx} = T_{rx} = 40ms$. It is assumed that the initial energy of sensor nodes is very large and does not degrade.

In WSNs, path loss is only related to the distance between the source and destination nodes; however, in UASNs with acoustic communication, both the distance and frequency affect the path loss. Fig.3 represents the energy consumption for node S_1 and node S_2 complete an interest and a data packet communication using direct transmission in shallow water. It can be seen in the figure that, when the frequency is fixed, energy consumption increases with the increasing communication distance between two nodes. In addition, with the same distance, if the frequency is higher, the energy consumed will also be greater. Fig.4 shows the consumption of an interest packet and a data packet transmitted between node S_1 to node S_2 using a direct connection path in deep water. When the distance is the same, if the frequency is higher, more energy will be expended. In addition, if the frequency is constant, the energy consumed increases with distance. As can be seen from the rising amplitude of the surface, distance and frequency have greater influence on energy consumption in deep water.

Figs.5 and 6 show the relationship between energy consumption and distance between nodes and frequency of data transmission in shallow water, respectively. It can be seen from the two graphs that energy consumption increases with both the increment of distance when data transmission frequency is fixed (Fig.5) and of the data transmission frequency when distance is fixed (Fig.6). Similar results can be obtained in deep water as shown in Figs.7 and 8, in which energy consumption also increases with the increment of distance and data transmission frequency. Therefore, the proposed energy consumption model verifies the argument that the energy consumption is related to both distance and frequency.

It is important to note that our relay selection criterion is based on a realistic relay network topology. The position of the relay node is determined by the values of θ_1 and θ_2. If $\theta_1 + \theta_2 = 1$, the relay node is on the straight link between the source and destination, whereas if $\theta_1 + \theta_2 > 1$, the three nodes are on the non-straight link. Under the condition that θ_1 and θ_2 are fixed, when $\Delta e = 0$ for formula (7), the distance is d_c, i.e., the critical value.

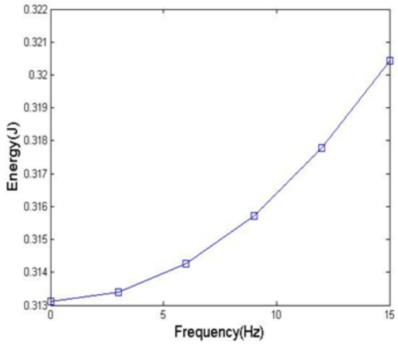


FIGURE 6. The relationship between energy consumption and frequency for a relay path in shallow water with fixed node distance.

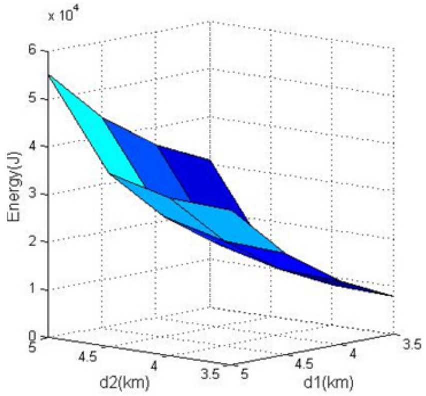


FIGURE 7. The relationship between energy consumption and node distance for a relay path in deep water with fixed frequency.

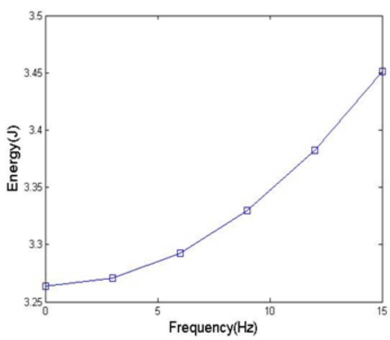


FIGURE 8. The relationship between energy consumption and frequency for a relay path in deep water with fixed node distance.

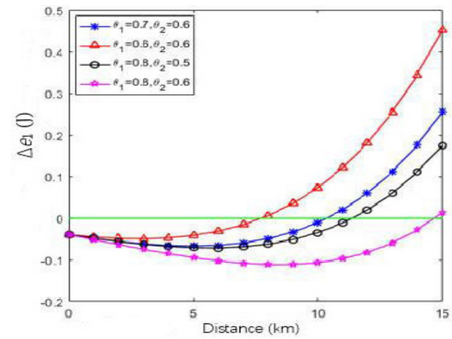


FIGURE 9. Energy consumption difference between direct path and relay path when f = 5 kHz in shallow water.

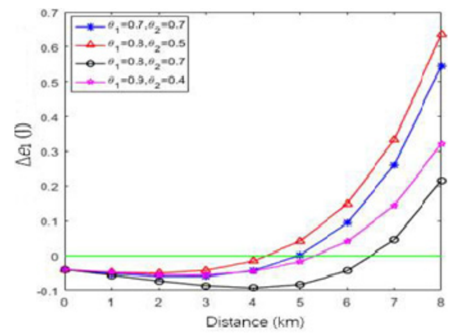


FIGURE 10. Energy consumption difference between direct path and relay path when f = 10 kHz in shallow water.

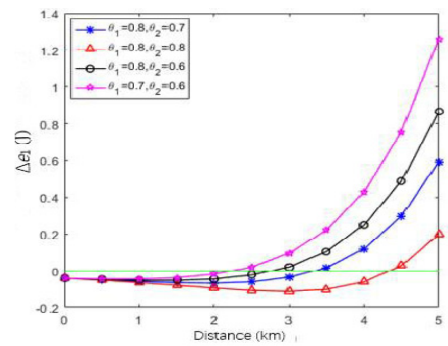


FIGURE 11. Energy consumption difference between direct path and relay path when f = 15 kHz in shallow water.

Figs.9 to 11 show the energy consumption difference in a shallow water scenario between the direct path and the relay path with different frequencies, which are $f = 5$ kHz, $f = 10$ kHz, and $f = 15$ kHz.Δe is marked as Δe_1 in shallow water and Δe_2 in deep water conditions. The horizontal green lines in the three graphs show that the energy consumptions of the relay path and the direct path are equal. The intersection point of the horizontal green line and other curves in each graph denotes the value of d_c. It can be seen from Fig.9 that when f is set to 5 kHz, and if θ_1 and θ_2 satisfy $\theta_1 + \theta_2 \geq 1.2$, and one of them is greater than 0.6, Δe_1 is negative with a distance of less than 8 km; this case indicates that direct transmission is preferable over relay transmission. It can be seen from Fig.10 that when f is set to 10 kHz, and if θ_1 and θ_2 satisfy $\theta_1 + \theta_2 \geq 1.4$ and one of them is greater than 0.7, data transmission on a direct path can save more energy than on a two-hop relay path when the distance is less than 4 km. Similarly, it can be seen from Fig.11 that when f is set as 15 kHz, and if θ_1 and θ_2 satisfy $\theta_1 + \theta_2 \geq 1.4$ and one of them is greater than 0.7, the direct path is preferable for distances of less than 2.5 km. In addition, the frequency can affect the data transmission distance, which indicates high frequency is more suitable for short distance data

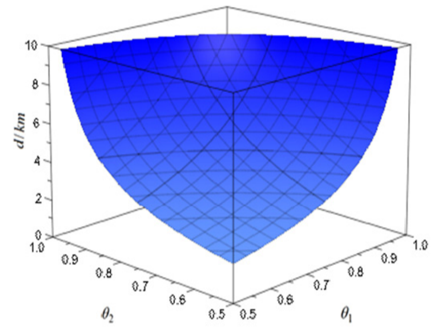


FIGURE 12. The critical value d_c difference with the variations of θ_1 and θ_2.

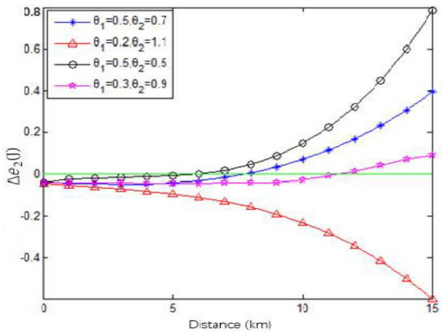


FIGURE 13. Energy consumption difference between direct path and relay path when f = 5 kHz in deep water.

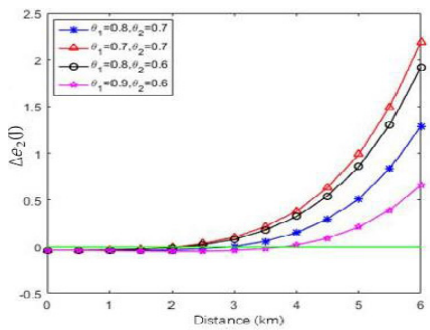


FIGURE 14. Energy consumption difference between direct path and relay path when f = 10 kHz in deep water.

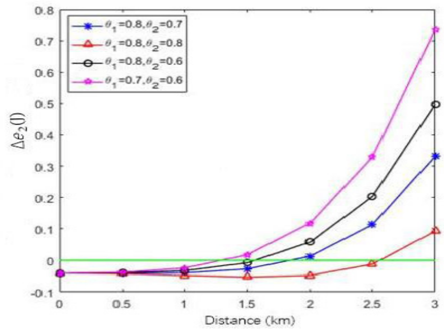


FIGURE 15. Energy consumption difference between direct path and relay path when f = 15 kHz in deep water.

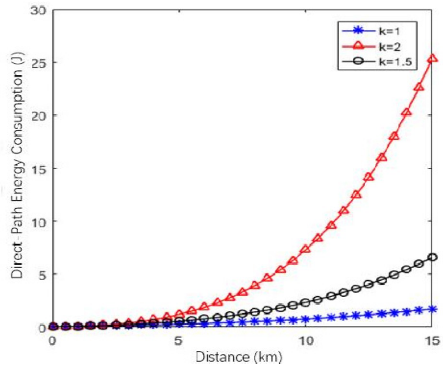


FIGURE 16. Energy consumption difference between deep and shallow water under direct path.

communication, while low frequency is more suitable for long distance data communication.

Fig.12 illustrates the relationship between the critical distance d_c and θ_1, θ_2 when the energy consumption of two nodes using a direct connection is equal to that using a relay. It can be seen from the figure that if both θ_1 and θ_2 are closer to 0.5, the value of d_c is smaller. This indicates that in all cases where the energy consumption of the relay path and the direct path are equal, and both θ_1 and θ_2 are closer to 0.5, energy consumption is minimal.

Figs.13 to 15 illustrate the energy consumption difference of the deep water scenario between the direct path and the relay path under different conditions. It can be seen from Fig.13 that when f is set to 5 kHz, and if θ_1 and θ_2 satisfy $\theta_1 + \theta_2 \geq 1.2$ and one of them is greater than 0.5, Δe_2 is negative with a distance of less than 5 km; this case means that direct transmission is preferable over relay transmission. It can be seen from Fig.14 that f is set to 10 kHz, and if θ_1 and θ_2 satisfy $\theta_1 + \theta_2 \geq 1.4$ and one of them is greater than 0.8, data transmission on a direct path can save more energy than on a two-hop relay path with a distance of less than 3 km. Similarly, it can be seen from Fig.15 that when f is set to 15 km, and if θ_1, θ_2 satisfy $\theta_1 + \theta_2 \geq 1.4$ and one of them is greater than 0.7, a direct path is preferable for distances of less than 1.5 km. From the graphs, it can be deduced that if the relay node position is unchanged under the same environment, the critical value will decrease with increasing frequency.

Fig.16 illustrates the difference in energy consumption based on direct transmission between the shallow water field and the deep water field with $f = 5$ kHz. When $d > 5$ km, the energy consumption in the deep water field exhibits exponential growth. In addition, the energy consumption difference increases when the distance increases.

Fig.17 presents the difference in energy consumption in shallow water between two paths with a variation of d_1 and d_2 under the conditions of $f = 10$ kHz and a distance of 10 km. It shows that the energy consumption can be minimized under the condition that the distances between the relay node and S_1 and S_2 are equal. The cross points of the curved surface

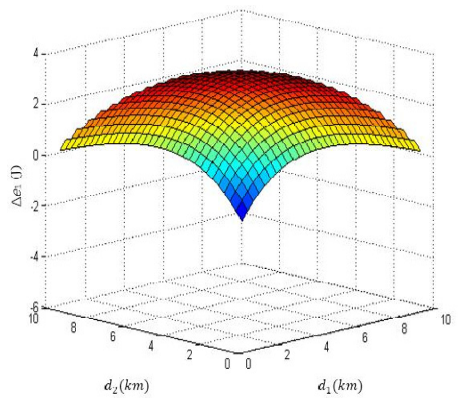


FIGURE 17. **Energy consumption difference in the direct path and relay path with the variations of d_1 and d_2 in shallow water.**

with $z = 0$ indicate that the energy consumption of the single-hop direct path and the two-hop relay path are equivalent. Moreover, in this case, the data transmission on the two-hop relay path can save more energy than on a single-hop direct path when $\Delta e_1 > 0$, while when $\Delta e_1 < 0$ a single-hop direct path is better. Therefore, it can be concluded that the location of the relay node has a great influence on the path selection. In the actual network structure, when a node dies, other relay nodes in the surrounding area can be selected to replace the failed nodes by using this strategy. The same conclusion can also be applied to deep water scenarios.

V. CONCLUSION

This paper presents an energy consumption model of NDN-based UASNs based on a relay topology that can be used for energy consumption calculations in both shallow and deep water fields. This study is an extension of ICN techniques applied in the WSN and IoT research fields, and can be regarded as a typical representation of an underwater IC-based IoT technique. The analysis shows the difference in energy consumption between single-hop direct path and two-hop relay path transmission in shallow and deep water. Further, the simulation verifies the effect of distance and frequency on energy consumption. According to the difference in energy consumption, the criterion of selection between the single-top direct path and two-hop relay path depends on the distance between nodes; the relay node position and frequency is obtained. The simulation shows that the energy is wasted when using relay nodes in short distance communication, and multi-hop relay transmission can increase the energy efficiency in long distance communication. In addition, the energy consumption model can also be extended to select an appropriate path for multi-hop nodes.

REFERENCES

[1] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, and S. Guizani, ''Internet-of-Things-based smart cities: Recent advances and challenges,'' *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 16–24, Sep. 2017.

[2] S. Sendra, J. Lloret, J. M. Jimenez, and L. Parra, ''Underwater acoustic modems,'' *IEEE Sensors J.*, vol. 16, no. 11, pp. 4063–4071, Jun. 2016.

[3] G. Xylomenos *et al.*, ''A survey of information-centric networking research,'' *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 1024–1049, 2nd Quart., 2014.

[4] L. Zhang *et al.*, ''Named data networking,'' *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 66–73, Jul. 2014.

[5] Z. Zhou, Z. Peng, J.-H. Cui, and Z. Shi, ''Efficient multipath communication for time-critical applications in underwater acoustic sensor networks,'' *IEEE/ACM Trans. Netw.*, vol. 19, no. 1, pp. 28–41, Feb. 2011.

[6] E. M. Sozer, M. Stojanovic, and J. G. Proakis, ''Underwater acoustic networks,'' *IEEE J. Ocean. Eng.*, vol. 25, no. 1, pp. 72–83, Jan. 2000.

[7] H. Li, K. Ota, and M. Dong, ''Energy cooperation in battery-free wireless communications with radio frequency energy harvesting,'' *ACM Trans. Embedded Comput. Syst.*, vol. 17, no. 2, p. 44, Feb. 2018.

[8] H. Li, K. Ota, and M. Dong, ''ECCN: Orchestration of edge-centric computing and content-centric networking in the 5G radio access network,'' *IEEE Wireless Commun.*, vol. 25, no. 3, pp. 88–93, Jun. 2018.

[9] H. Li, K. Ota, M. Dong, and H.-H. Chen, ''Efficient energy transport in 60 GHz for wireless industrial sensor networks,'' *IEEE Wireless Commun.*, vol. 24, no. 5, pp. 143–149, Oct. 2017.

[10] J. Xu, K. Ota, and M. Dong, ''Saving energy on the edge: In-memory caching for multi-tier heterogeneous networks,'' *IEEE Commun. Mag.*, vol. 56, no. 5, pp. 102–107, May 2018.

[11] G. Xie, K. Ota, M. Dong, F. Pan, and A. Liu, ''Energy-efficient routing for mobile data collectors in wireless sensor networks with obstacles,'' *Peer-Peer Netw. Appl.*, vol. 10, no. 3, pp. 472–483, May 2017.

[12] J. Long, M. Dong, K. Ota, and A. Liu, ''A green TDMA scheduling algorithm for prolonging lifetime in wireless sensor networks,'' *IEEE Syst. J.*, vol. 11, no. 2, pp. 868–877, Jun. 2017.

[13] O. Hahm, E. Baccelli, T. Schmidt, M. Wählisch, C. Adjih, and L. Massoulié, ''Low-power Internet of Things with NDN & cooperative caching,'' in *Proc. ACM 4th ACM Conf. Inf.-Centric Netw.*, 2017, pp. 98–108.

[14] B. Chen, L. Liu, Z. Zhang, W. Yang, and H. Ma, ''BRR-CVR: A collaborative caching strategy for information-centric wireless sensor networks,'' in *Proc. 12th Int. Conf. Mobile Ad-Hoc Sensor Netw. (MSN)*, Hefei, China, Dec. 2016, pp. 31–38.

[15] Y. Song, H. Ma, and L. Liu, ''Content-centric Internetworking for resource-constrained devices in the Internet of Things,'' in *Proc. IEEE Int. Conf. Commun. (ICC)*, Budapest, Hungary, 2013, pp. 1742–1747.

[16] M. Amadeo, C. Campolo, A. Molinaro and N. Mitton, ''Named data networking: A natural design for data collection in wireless sensor networks,'' in *Proc. IEEE IFIP Wireless Days (WD)*, Nov. 2013, pp. 1–6.

[17] J. Xu, K. Li, and G. Min, ''Reliable and energy-efficient multipath communications in underwater sensor networks,'' *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 7, pp. 1326–1335, Jul. 2012.

[18] R. Hou, L. He, S. Hu, and J. Luo, ''Energy-balanced unequal layering clustering in underwater acoustic sensor networks,'' *IEEE Access*, vol. 6, no. 1, pp. 39685–39691, 2018.

[19] X. Li, Y. Wang, and J. Zhou, ''An energy-efficient clustering algorithm for underwater acoustic sensor networks,'' in *Proc. Int. Conf. Control Eng. Commun. Technol. (ICCECT)*, Dec. 2012, pp. 711–714.

[20] Y. Li, Y. Wang, Y. Ju, and R. He, ''Energy efficient cluster formulation protocols in clustered underwater acoustic sensor networks,'' in *Proc. 7th Int. Conf. Biomed. Eng. Inform.*, Oct. 2014, pp. 923–928.

[21] R. Su, R. Venkatesan, and C. Li, ''Balancing between robustness and energy consumption in underwater acoustic sensor networks,'' in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2015, pp. 1048–1053.

[22] R. Hou and M. Zheng, ''Packet-based nonlinear battery energy consumption optimizing for WSNs nodes,'' *IEICE Electron. Express*, vol. 11, no. 9, 2014, Art. no. 20140167.

[23] R. Hou, M. Zheng, Y. Chang, and Q. Zhang, ''Analysis of battery energy consumption in wireless sensor networks considering path correlation,'' *Sensor Lett.*, vol. 13, no. 3, pp. 240–244, 2015.

[24] W. Zhang, D. Duan, and L. Yang, ''Relay selection from a battery energy efficiency perspective,'' *IEEE Trans. Commun.*, vol. 59, no. 6, pp. 1525–1529, Jun. 2011.

[25] R. Tian and R. Hou, ''Analysis of battery energy consumption in relay wireless sensor networks,'' *IET J. Eng.*, vol. 2016, no. 8, pp. 294–297, 2016.

[26] R. Hou, Y. Chen, and G. Xing, ''Path selection for optimizing nonlinear battery energy consumption,'' *IEICE Electron. Express*, vol. 10, no. 22, 2013, Art. no. 20130689.

[27] M. C. Domingo and R. Prior, "Energy analysis of routing protocols for underwater wireless sensor networks," *Comput. Commun.*, vol. 31, no. 6, pp. 1227–1238, 2008.
[28] A. Sehgal, C. David, and J. Schönwälder, "Energy consumption analysis of underwater acoustic sensor networks," in *Proc. OCEANS MTS/IEEE KONA*, Waikoloa, HI, USA, Sep. 2011, pp. 1–6.
[29] P. Wang and X. Zhang, "Energy-efficient relay selection for QoS provisioning in MIMO-based underwater acoustic cooperative wireless sensor networks," in *Proc. 47th Annu. Conf. Inf. Sci. Syst. (CISS)*, Baltimore, MD, USA, Mar. 2013, pp. 1–6.
[30] A. Khan, M. Ejaz, N. Javaid, M. Q. Azeemi, U. Qasim, and Z. A. Khan, "EEORS: Energy efficient optimal relay selection protocol for underwater WSNs," in *Proc. 19th Int. Conf. Netw.-Based Inf. Syst. (NBiS)*, Ostrava, Czech Republic, Sep. 2016, pp. 239–245.
[31] H. Ghafoor, Y. Noh, and I. Koo, "OFDM-based spectrum-aware routing in underwater cognitive acoustic networks," *IET Commun.*, vol. 11, no. 17, pp. 2613–2620, Nov. 2017.
[32] X. Li, J. Liu, L. Yan, S. Han, and X. Guan, "Relay selection for underwater acoustic sensor networks: A multi-user multi-armed bandit formulation," *IEEE Access*, vol. 6, pp. 7839–7853, 2018.
[33] Y. Wei and D.-S. Kim, "Exploiting cooperative relay for reliable communications in underwater acoustic sensor networks," in *Proc. IEEE Mil. Commun. Conf.*, Baltimore, MD, USA, Oct. 2014, pp. 518–524.
[34] L. Liu, M. Ma, C. Liu, and Y. Shu, "Optimal relay node placement and flow allocation in underwater acoustic sensor networks," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 2141–2152, May 2017.

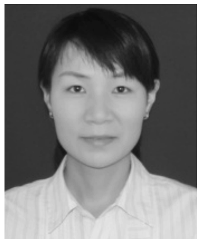
GUANGLIN XING received the B.Eng. and M.E. degrees in computational mathematics and software from Wuhan University, in 1995 and 1998, respectively, and the Ph.D. degree in computer software and theory from the Huazhong University of Science and Technology, in 2005. He is currently an Associate Professor with the College of Computer Science, South-Central University for Nationalities, Wuhan, China. He has authored or coauthored over 50 papers in international journals and conferences. His main research interests include routing optimization and energy efficiency in wireless sensor networks.

YUMENG CHEN is currently pursuing the M.Eng. degree with the College of Computer Science, South-Central University for Nationalities, Wuhan, China. His area of research is wireless sensor networks.

LIUTING HE is currently pursuing the M.Eng. degree with the College of Computer Science, South-Central University for Nationalities, Wuhan, China. Her areas of research interest are wireless sensor networks and information-centric networking.

WANYAN SU is currently pursuing the M.Eng. degree with the College of Computer Science, South-Central University for Nationalities, Wuhan, China. Her area of research is energy efficiency in wireless sensor networks.

RUI HOU received the B.Eng, B.L, and M.E. degrees in mechanics, economic law, and physical electronics from Wuhan University, China, in 2000, 2000, and 2003, respectively, and the Ph.D. degree in optical engineering from the Huazhong University of Science and Technology, Wuhan, in 2006. From 2003 to 2006, he was a Research Staff Member with the Wuhan National Laboratory for Optoelectronics. He conducted research in the Signaling, Communications, and Networking Laboratory, Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO, USA, from 2014 to 2015. He is currently a Professor with the College of Computer Science, South-Central University for Nationalities, Wuhan. He was sponsored by the Chinese Scholarship Council as a National Senior Visiting Scholar. He has authored or coauthored over 100 papers in international journals and conferences. He has also served as a Reviewer for more than 30 international journals and conferences. His main research interests include next-generation computer network architectures, WDM networks, and wireless sensor networks. He is a member of IEICE, OSA, and CCF.



WEI LI received the B.Eng. degree in instrument science from the Hefei University of Technology, Hefei, China, in 2005, and the Ph.D. degree from the Huazhong University of Science and Technology, Wuhan, China, in 2010. From 2012 to 2016, she was a Postdoctorate with the State Key Laboratory of Coal Combustion. She is currently a Lecturer with the College of Computer Science, South-Central University for Nationalities, Wuhan. She has authored or coauthored over ten journals and conference papers. Her current research interests include network system modeling and simulation.

CHENGJUN ZHANG received the B.Eng and M.E. degrees in mechanical engineering from the Hubei University of Technology, Wuhan, China, in 2002 and 2006, respectively, and the Ph.D. degree in material processing engineering from the Huazhong University of Science and Technology, Wuhan, in 2014. He is currently an Associate Professor with the College of Mechanical Engineering and Automation, Wuhan Textile University, Wuhan. He was sponsored by the Hubei Provincial Education Department, College of Science, Technology and Agriculture, Cape Girardeau, MO, USA, as a Visiting Scholar, from 2016 to 2017. He has authored or coauthored over 60 papers in international journals and conferences. His main research interests include next-generation computer network architectures and new integrated circuit design.

XIQU CHEN received the B.S. degree in automation from Xi'an Highway University, in 1995, and the M.S. and Ph.D. degrees in physical electronics from the Huazhong University of Science and Technology, in 2003 and 2007, respectively. He has authored or coauthored over 30 papers in international journals and conferences. His current research interests include sensors and signal processing in wireless sensor networks.