Research Article

A QoS-Based Topology Control Algorithm for Underwater Wireless Sensor Networks

Linfeng Liu

School of Computer, Nanjing University of Posts and Telecommunications, Nanjing 210003, China

Correspondence should be addressed to Linfeng Liu, liulf@njupt.edu.cn

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The topology control techniques of underwater wireless sensor networks and terrestrial wireless sensor networks are significantly different because of the particularity of underwater environments and acoustic communication. In this paper, an underwater wireless sensor network model was constructed, and six universal topology control objectives were concluded. The QoS topology control problem was mapped into an ordinal potential game model, and a distributed strategy adjustment algorithm for nodes was designed accordingly. The strategy vector resulting from the algorithm converges to the Nash equilibrium; minor complexity and preferable approximate ratios can be represented by the algorithm as well. The performance of the algorithm was analyzed through simulation experiments which indicate a well-constructed topology. Every objective was upgraded when model parameters were set suitable.

1. Introduction

Recently, there has been growing interest in the application of sensor networks in underwater environments to enable and enhance applications such as ocean resource exploration, pollution monitoring, and tactical surveillance [1–3]. Before the emergence of wireless sensor networks (WSNs) [4], the perception and collection of underwater data are generally accomplished through wired networks which are very costly. Underwater wireless sensor networks (UWSNs) [5–7] are the enabling technology for these underwater applications. UWSNs consist of sensors that perform collaborative monitoring tasks over a three-dimensional volume. Acoustic communications [8, 9] are the typical physical layer technology in underwater networks. There are three types of nodes in UWSNs: bottom nodes, anchored nodes, and surface sinks. The given phenomenon is observed by interconnected bottom and anchored nodes in charge of relaying data to surface sinks. The architecture of a UWSN is depicted in Figure 1.

Figure 1 illustrates a three-dimensional UWSN; each bottom or anchored node can monitor and detect environmental events locally, and then transfer these measurements to a surface sink by multihops. Bottom nodes are spread on the seabed. Anchored nodes are equipped with floating buoys that can be inflated by pump. The depth of the anchored node can be regulated by adjusting the length of the wire.

QoS is an important issue in WSNs because quality of service has immediate impact on the availability of networks, and topology control is one of the main techniques to improve the quality of WSN service. Due to the specificity and complexity of the water medium, UWSN and terrestrial wireless sensor networks are significantly different. These differences include the following: (a) the propagation delay of the acoustic wave is much larger than that of the electromagnetic wave, and the propagation delay in UWSN cannot be neglected. (b) The limited bandwidth of underwater acoustic links is prone to cause high error rates and frequent dynamics of topology [10]. (c) Underwater acoustic communication requires more energy for signal modulation, and the energy consumption for sending messages is significantly larger than that for receiving. These differences make it difficult to guarantee the quality of the service (e.g., propagation delay, bandwidth, and transmission success rate) in UWSNs. In this regard, topology control is an efficient way to enhance the quality of services. In addition to the common topology control objectives of WSNs (full coverage, network connectivity, decrease in energy consumption, enhancement of network capacity, reduction of communication interference, and increase of spatial reuse), the topology control
objectives in UWSN should also include the shortening of propagation delay, improvement of energy consumption efficiency, extension of network lifetime, augmentation of transmission bandwidth, and increase in the transmission success rate. Therefore, in this paper QoS-based topology control for UWSN is defined as the art of coordinating nodes’ decisions regarding their communication and sensing ranges, in order to generate a network topology with the desired properties (e.g., connectivity, coverage), while optimizing some (or all) of other service metrics (e.g., energy consumption, propagation delay, transmission bandwidth, and transmission success rate) in underwater environments.

The remainder of this paper is organized as follows. In Section 2, we discuss related works; in Section 3, we describe the UWSN model and define some concepts; in Section 4, we map QoS topology control problem into an ordinal potential game model; Section 5 proposes a strategy adjustment algorithm SAA; in Section 6, SAA is analyzed from the aspects of convergence, complexity, and approximate ratio; in Section 7, we discuss the performance evaluation of SAA; finally, Section 8 provides some conclusions.

2. Related Work

The problem of QoS topology control for WSN has been extensively studied. However, most studies have been based on specific applications or partial objectives. Furthermore, the characteristics of acoustic communication and underwater environments have never been taken into account. Li et al. [11] proposed an MST-based topology control algorithm (LMST) that can effectively reduce transmission power while maintaining global connectivity. However, the topology obtained by LMST is fragile, and network lifetime is prone to termination. In a study by Li et al. [12], the QoS topology control problem in heterogeneous ad hoc networks was formulated as an integer linear programming problem or a mixed integer linear programming problem. This produced a network topology that meets QoS requirements and minimizes the maximum energy utilization of nodes. Liu et al. [13] reported that each node in the network has different functionalities in data transmission, and they correspondingly proposed a topology control algorithm (EasiTPQ) to improve packet loss rate and propagation delay. Cai and Yang [14] presented a multi-QoS optimization distributed topology control algorithm (MQOTC) considering residual energy, end-to-end delay, and link loss ratio; every sensor node builds the local maximum QoS topology independently. MQOTC is distributed and is scalable, but it does not consider the full coverage objective, and it cannot be adapted when the requirements of specific applications change. To ensure high QoS (maximizing network lifetime and ensuring message delivery), a topology control algorithm (EBC) which exploits the edge of the centrality concept is proposed [15]. In the investigation conducted by Ma et al. [16], both centralized and distributed QoS topology control approaches employing opportunistic transmission are put forward; simulations demonstrate that the approach significantly improves energy efficiency with low communication overhead. Forghani et al. [17] improved network lifetime and decreased average energy consumption by reducing the transmission power of nodes and periodically choosing the active path. However, the approach ignores the extra overhead brought by the periodical regulation of active paths. Reference [18] proposed a framework, based on the emergent potential games to deal with a variety of network resource allocation problems. But the framework was designed for terrestrial wireless sensor networks, and some basic topology requirements (e.g., coverage) were not taken into account. An energy-efficient topology control algorithm FiYG was proposed in [19]. FiYG was designed
for three dimensional UWSNs, but it was unable to achieve typical underwater QoS objectives.

In summary, the existing algorithms or approaches of QoS topology control are difficult to apply in UWSN because of the following. (a) Currently, the QoS topology control objectives of UWSN have not been analyzed intensively. Therefore, some important objectives in underwater environments have been neglected. (b) Due to the multiformity of UWSN applications, different QoS objectives will be required in different applications. The QoS topology control model and algorithm should be capable of objective-driven adaptation. (c) Most current studies assume that the deployment space is a two-dimensional plane. However, underwater topography is complicated, and so the deployment space must be three dimensional.

Inspired by such motivations, the QoS topology control for UWSN is investigated in this paper by exploiting the ordinal potential game model. Given an amount of wireless sensor nodes in a 3D space where nodes have a set of strategies (i.e., different communication radiiuses and sensing radiiuses) and given the capacities of energy consumption, propagation delay, bandwidth, and transmission success rates on links, the aim is to find a UWSN topology that can meet both full coverage and global connectivity while optimizing other objectives as much as possible.

3. UWSN Model

Our work is based on the scenario that a set of static sensors are deployed in underwater space $D \subseteq 1R^3$. The topology of UWSN can be represented as a graph $G(V,E)$, where the finite set of nodes $V = \{V_1,V_2,\ldots,V_N\}$ and the set of links $E \subseteq V \times V$.

3.1. Model Description

1. Nodes. For all $V_k \in V$, its current communication radius, sensing radius, and residual energy are denoted as $RC(k)$, $RS(k)$, and $e(k)$, respectively. Any node $V_k$ can be in two kinds of status: awake or asleep. If $V_k$ is asleep, then $RS(k) = RC(k) = 0$. The set of awake nodes $W = \{V_k | V_k \in V, RS(k) > 0, RC(k) > 0\}$. For all $V_k, V_j \in V$ or for all $p,q \in D$, the distance is $d(k,k')$ and $d(p,q)$. We define the neighboring nodes set of $V_k$ as $ne(k)$ and $ne(k) = \{V_k' | d(k,k') \leq RC(k)\}$.

2. Links. For all $V_k' \in ne(k)$, the link between $V_k$ and $V_k'$ is expressed as $(k,k')$. The propagation delay, bandwidth, and transmission success rate of $(k,k')$ are denoted as $delay(k,k'), band(k,k')$, and $ratio(k,k')$ respectively. For all $V_i, V_j \in V$ if $d(i,j) \leq RC(i)$, then $(i,j) \in E$.

3. Paths. For all $V_i, V_j \in V$ if there are $(i,i_1),(i_1,i_2),\ldots,(j_2,j_1),(j_1,j) \in E$, then path$(i,j)$ exists.

3.2. Definitions and Assumptions. Suppose that $X$ is a set of Boolean values, and $R$ is a set of positive real numbers. UWSN coverage function is expressed as coverage($G$): $G(V,E) \rightarrow X$, the connectivity function is defined as

$connectivity(G): G(V,E) \rightarrow X$, and the energy consumption function of the node is consumption($k$): $VK \rightarrow R$, with $V_k \in W$. To clarify and simplify the UWSN model, other definitions and assumptions are given.

Definition 1. Node coverage space: for all $V_k \in V$, coverage space of $V_k$ with sensing radius $RS(k)$ defined as $Cover(k,RS(k)) = \{p | d(k,p) \leq RS(k), \text{ for all } p \in D\}$.

Definition 2. Bidirectional links: for all $V_i, V_j \in V$ if $d(i,j) \leq RC(i)$ and $d(i,j) \leq RC(j)$, then link $(i,j)$ is bidirectional.

Definition 3. Full coverage: for all $p \in D$, there exist $V_k \in W$, with $d(k,p) \leq RS(k)$.

Definition 4. Global connectivity: for all $V_i, V_j \in W$, path$(i,j)$ and path$(j,i)$ exist.

Definition 5. Alive status of UWSN: full coverage and global connectivity can be achieved by awake nodes set $W$, and for all $V_k \in W, e(k) > 0$.

Assumption 1. Sensor nodes are uniformly distributed in $D$, and the coordinates of every node have been informed.

Assumption 2. $D$ is a convex region, for all $p,q \in D$, we get $a\overline{p} + (1-a)\overline{q} \in D \ (0 \leq a \leq 1)$.

Assumption 3. $RC_1 \geq 2RS_\chi$. $RC_1$ denotes the minimum communication radius, and $RS_\chi$ denotes the maximum sensing radius.

Assumption 4. For all $V_k \in V$, $V_k \in ne(k)$, delay($k,k'$), band($k,k'$) and ratio($k,k'$) are known values.

Assumption 5. If for all $V_k \in V$, then $RC(k) = RC_\chi$ and $RS(k) = RS_\chi$; therefore, $G(V,E)$ satisfies both full connectivity and global connectivity.

3.3. Objectives. The QoS topology control objectives of UWSN can be presented as

(i) $coverage(G) = 1$,
(ii) $connectivity(G) = 1$,
(iii) $\min \sum_{V_k \in V} consumption(k)$,
(iv) $\min \sum_{V_k, V_j \in W} \sum_{i,j \in \text{path}(i,j)} \text{delay}(i,j)$,
(v) $\max \sum_{V_k, V_j \in W} \min_{i,j \in \text{path}(i,j)} \text{band}(i,j)$,
(vi) $\max \sum_{V_k, V_j \in W} \prod_{i,j \in \text{path}(i,j)} \text{ratio}(i,j)$.

Objectives (i) and (ii) should be strictly satisfied, and objectives (iii)–(vi) are optimized as much as possible. The QoS topology control problem with multiobjective optimization is a NP-hard problem which will be solved approximately by the ordinal potential game in the next section.

4. Ordinal Potential Model

4.1. Game Description. Game theory attempts to mathematically capture behavior in strategic games, in which
Table 1: Description of symbols in the game model.

| Symbol | Description                                      | Symbol | Description                                      |
|--------|--------------------------------------------------|--------|--------------------------------------------------|
| A      | Strategy space                                   | A_k    | Optional strategies set of V_k                  |
| A_k    | Strategy vector                                  | A_k^-  | Strategies set of non-V_k nodes                 |
| a      | Selected strategy of V_k                         | U(a)   | Payoff function vector                           |
| a_k    | Strategy vector of non-V_k nodes                 | u_k(a) | Payoff function of V_k                           |
| RC_p   | ψth level communication radius                   | χ      | Number of optional strategies                    |
| RC_p   | ψth level sensing radius                         | C_k(a) | Coverage function of V_k                         |
| RS_p   | ψth level sensing radius                         | D_k(a) | Propagation delay function of V_k                |
| E_k(a) | Energy consumption function of V_k               | S_k(a) | Transmission success rate function of V_k        |
| B_k(a) | Bandwidth function of V_k                        |        |                                                  |

Lemma 6. When RC_1 ≥ 2RS_p, if UWSN covers the convex region D, then G(W, E) satisfies global connectivity.

Proof. The proof is similar with Theorem 7 in a study by Wang et al. [25]; for any two nodes V_i and V_j, W_j, P_j is the line segment joining V_i and V_j. Due to the coverage of UWSN, any point p ∈ P_j has been covered by at least one close and awake sensor node. Consequently, the set of closest nodes s_1,...,s_m can be constructed for contiguous segments which consist of points with the same set of closest sensors. For all u ∈ s_k−1, v ∈ s_k, we have d(u, v) ≤ RS(u) + RS(v). We assume RS(u) ≥ RS(v), which directly yields RC(u) ≥ RC(v) and d(u, v) ≤ 2RC(υ) ≤ 2RC(υ). Hence, both (u, v) and (υ, u) are bidirectional links, and there must be path(i, j) between V_i and V_j.

(a) Coverage Function. Any node V_k has a coverage function

\[ C_k(a) = \prod_{v \in V} F_i(a) \tag{5} \]

Formula (5) shows that the coverage function is the product of all nodes’ local coverage functions. F_i(a) is defined as the local coverage function of node V_i

\[ F_i(a) = \begin{cases} 1 & \text{if } \exists V_j \in W, d(j, p) \leq RS(j), \\ 0, & \text{else}. \end{cases} \tag{6} \]

Formula (6) means all points in every node’s possible maximum coverage area should be covered by at least another node.

Theorem 7. Full coverage can be achieved when C_k(a) = 1.

Proof. ∴ C_k(a) = 1, ∴ for all V_i ∈ V, F_i(a) = 1, ∴ for all p ∈ \bigcup_{V_i \in V} (D ∩ Cover(i, RS_i)), there exist V_j ∈ W, d(i, j) ≤ RS(j). Assumption 5 gives D ⊆ \bigcup_{V_i \in V} Cover(i, RS_i); therefore, for all p ∈ D, there exist V_j ∈ W, d(j, p) ≤ RS(j).
(b) Energy Consumption Function. For any node $V_k$, the energy consumption function

$$E_k(a) = E_k(a_k, a_{-k})$$

$$= P_0(a_k)$$

$$= P_0 RC(k) \beta 10^{RC(k) a(f)/10},$$

where $P_0$ is the least received power level to guarantee the required quality of reception [26], and $(a_k)$ is signal attenuation [27]. The energy spreading factor and absorption coefficient are denoted by $\beta (\beta \in [1,2])$ and $a(f)$, respectively.

(c) Propagation Delay Function. Suppose that the number of neighboring nodes is $k$ in $V_k$ with strategy $a_k$, then $D_k(a)$ can be expressed as

$$D_k(a) = D_k(a_k, a_{-k}) = \frac{\sum_{V_i \in ne(k)} \text{delay}(k, k')}{k},$$

where delay$(k, k')$ [28] is computed as

$$\text{delay}(k, k') = \frac{L}{B} + \frac{d(k, k')}{R_{raw}},$$

where $L$ is the length of every data packet, $B$ is the channel capacity in bits per second, and $R_{raw}$ is the propagation speed of underwater sound. Thus,

$$D_k(a_k, a_{-k}) = \frac{\sum_{V_i \in ne(k)} d(k, k')}{kR_{raw}} + \frac{L}{B},$$

where $L$ is the length of every data packet, $B$ is the channel capacity in bits per second, and $R_{raw}$ is the propagation speed of underwater sound. Thus,

(d) Bandwidth Function

$$B_k(a) = B_k(a_k, a_{-k}) = \min_{V_i \in ne(k)} \text{band}(k, k').$$

(e) Transmission Success Rate Function

$$S_k(a) = S_k(a_k, a_{-k}) = \left( \prod_{V_i \in ne(k)} \text{ratio}(k, k') \right)^{1/k},$$

where ratio$(k, k') \in [0,1]$, and $S_k(a) \in [0,1]$.

Theorem 8. $\Gamma(V, A, U(a))$ is an ordinal potential game.

Proof. The ordinal potential function is defined as

$$\tilde{U}(a) = \sum_{V_i \in W} u_i(a)$$

and let $\Delta u_k = u_i(a_k, a_{-k}) - u_i(b_k, a_{-k})$ which gives

$$\Delta \tilde{U} = \tilde{U}(a_k, a_{-k}) - \tilde{U}(b_k, a_{-k}) = \Delta u_k$$

$$+ \sum_{V_i \in W : i \neq k} \left\{ C_i(a_k, a_{-k}) - C_i(b_k, a_{-k}) \right\}.$$

The proof is similar to the one in previous reports [29].

Definition 9. Nash Equilibrium (NE): $a^*$ is NE if for all $V_k \in V$, for all $a_k \in A_k$, and $u_i(a^*) \geq u_i(a_k, a^*_{-k}).$

Potential games are known to possess at least one NE in pure strategies as proven in previous reports [29].

5. Algorithm

In this section, a distributed strategy adjustment algorithm (SAA) is proposed for nodes to achieve objectives (i) and (ii) while optimizing objectives (iii)–(vi) approximately. The following are the description and pseudocode of the SAA algorithm.
Table 3: Inquire_msg/feedback_msg structure.

| Message information | Node information | Neighbor information |
|---------------------|------------------|----------------------|
| Type                | ID   | Position | Strategy | Adjust | ID_Set | Local coverage |

**Strategy Adjustment Algorithm (SAA)**

**Step 1.** Any node $V_i$ has an initial strategy set as $a_i^{(0)} = (RC_{p_i}, R_{S_i})$; the adjustment function of $V_i$ is defined and initialized as $H(i) = 0$. After the initial setting, every node with maximum communication radius $RC_x$ broadcasts the message `announce_msg` whose structure is depicted in Table 2.

**Step 2.** If one node receives `announce_msg`, then it replies with `receive_msg` (Table 2).

**Step 3.** At the $\xi$th round, the node which will adjust the strategy is selected randomly from the probability formula

$$P_i(\xi) = \begin{cases} 0 & \text{if } H(i) \neq 0, \\ \frac{\Delta u_i(a_i^{(\xi-1)})}{\sum_{V_j \in V_i, H(j) = 0} \Delta u_j(a_j^{(\xi-1)})} & \text{else,} \end{cases}$$

(14)

where for $V_i$ at the $\xi$th round, $P_i^{(\xi)}$ denotes the probability of becoming the only strategy adjustment node, and $\Delta u_i(a_i^{(\xi-1)})$ is the possible payoff enhancement which is computed as

$$\Delta u_i(a_i^{(\xi-1)}) = \max_{b_i \in A_i} \left( u_i(b_i, a_i^{(\xi-1)}) - u_i(a_i, a_i^{(\xi-1)}) \right).$$

(15)

For any node $V_i$, if $H(i) = 0$, $V_i$ should broadcast a message `inquire_msg` in the spheriform range of radius $RC_x$. Suppose that $V_j$ receives `inquire_msg` from $V_i$, $V_j$ will compute all possible $F_j(a)$ when it adopts different strategies. Subsequently, a message `feedback_msg` containing all possible values of $F_j(a)$ will be replied to $V_i$. The structures of `inquire_msg` and `feedback_msg` are shown in Table 3.

The strategy of $V_i$ should be updated according to Expression (16) provided that $V_i$ has been chosen to adjust its strategy at the $\xi$th round; following this, the adjustment function must be set as $H(i) = \xi$

$$a_i^{(\xi)} = \arg \max_{b_i \in A_i} u_i(b_i, a_i^{(\xi-1)}).$$

(16)

**Step 4.** Upon completion of the strategy adjustment, the last round broadcasts `announce_msg`.

**Step 5.** Steps 1 to 4 are repeated for $N$ rounds.

The pseudocode of SAA is given in Pseudocode 1.

6. Algorithm Analysis

6.1. Convergence. SAA is theoretically proven to be convergent.

**Theorem 10.** SAA converges to NE.

*Proof.* For all $V_i \in V$, the minimum sensing radius of $V_i$ to achieve full coverage is denoted as $\Phi(a_{-i})$, a monotonic, nonincreasing function of $a_{-i}$, that is, if $a_{-i}^{k_1} = (RC(k_1), RS(k_1)), a_{-i}^{k_2}$ and $a_{i}^{k_2} = (RC(k_2), RS(k_2)), a_{-i}^{k_2}$, then $\Phi(a_{-i}^{k_1}) \leq \Phi(a_{-i}^{k_2})$. Accordingly, the value interval of sensing radius $R(a_{-i}) = \{\Phi(a_{-i}), \ldots, (RC_{p_i}, R_{S_i})\}$. To adjust the strategy of $V_i$, Expression (16) can be rewritten as

$$\tilde{a}_i = \{ (RC_{p_i}, R_{S_i}) R_{S_i} \geq \Phi(a_{-i}), \ \max u_i(\tilde{a}_i, a_{-i}) \}. \tag{17}$$

After strategy update, the payoff of $V_i$ will be maximized with the strategy vector $(\tilde{a}_i, a_{-i})$; if $V_j$ updates strategy to $\tilde{a}_i$ as well, there must be $RS(j) \leq RS_{p_i}$. $\Phi(\tilde{a}_j, a_{-i}) \geq \Phi(a_{-i})$ and $\tilde{a}_i \in R(\tilde{a}_i, a_{-i})$. In this case, the new strategy vector $(\tilde{a}_i, \tilde{a}_j, a_{-i})$ continues to maximize the payoff of $V_i$. Therefore, the result of SAA execution $\tilde{a} = (\tilde{a}_i, \tilde{a}_2, \ldots, \tilde{a}_n)$ is determinately NE.

6.2. Complexity. For any node $V_i$, even though $V_i$ changes strategy, the $F_j(a)$ of any node $V_j$ out of the spheriform range with center $V_i$ and radius $RC_i$ remains the same.

**Theorem 11.** For all $V_i, V_j \in V$, if $d(i,j) \geq RC_1$, no point $p \in D \cap \text{Cover}(i, RS_i)$ can be found to satisfy $d(i, p) \leq RS_2$.

*Proof.* Suppose that there exist $p \in D \cap \text{Cover}(i, RS_i)$ and $d(i,p) \leq RS_2, d(i, p) \leq RS_2$ which gives $d(i,j) \leq d(i,p) + d(j,p) \leq 2RS_2 \leq RC_1$. This conclusion contradicts the premise $d(i,j) \geq RC_1$.

The implementation and operating cost of algorithm realization can be measured with algorithm complexity.
of the parameters are shown in Table 4. Moreover, node connectivity and coverage increase until 100% regardless of 
the deployment density of nodes must be large enough to achieve full coverage and global connectivity; (b) the plot of 
connectivity and coverage increase until 100%. Figure 2 illustrates the connectivity and coverage of UWSN as N increases; the value of χ is assigned as 5, 7, and 10. Three observations can be made: (a) as N increases, both connectivity and coverage increase until 100% regardless of 
the value of χ. The reason for such behavior is that the deployment density of nodes must be large enough to achieve full 
coverage and global connectivity; (b) the plot of χ = 10 is higher than the other two plots because the growth of 
χ augments the maximal communication radius and the sensing radius, acquiring higher connectivity and coverage; 
(c) the least number of nodes required for full coverage (N = 1200 at χ = 10) is far more than what is required for 
global connectivity (N = 300 at χ = 10). This phenomenon confirms the conclusions of Lemma 6 (full coverage is a 
sufficient condition of global connectivity).
7.2. Average Energy Consumption. Set $\varphi_1 = 0.4$ and $\varphi_2 = \varphi_3 = \varphi_4 = 0$. This simulation compares the average energy consumption and UWSN lifetime in SAA, FiYG, LMST, and EBC. As shown in Figure 3, the SAA average energy consumption of the node in unit time is significantly lower than those of FiYG, LMST, and EBC. This is because the topology control model can be transformed into a QoS model aiming at low energy consumption. By setting the parameters, SAA can effectively reduce the average energy consumption of nodes. In Figure 3, the plots decrease as $N$ increases, which is attributed to the fact that full coverage and global connectivity can be met by nodes with a relatively lower strategy rank as more nodes are densely deployed.

Furthermore, from Figure 4, UWSN lifetime apparently increases as $N$ increases, and the UWSN lifetime obtained by SAA is higher than those by other algorithms.

7.3. Average Delay of Single Hop. Set $\varphi_2 = 0.2$ and $\varphi_1 = \varphi_3 = \varphi_4 = 0$. In Figure 5, the average delay of single hop in SAA is lower than that in FiYG, LMST, and EBC. There is a 4.2 ms difference between SAA and LMST when $N = 3000$. As $N$ increases, the average delay of single hop of all algorithms gradually shortens due to increasing deployment density.

7.4. Influence of $\varphi_1$ and $\varphi_2$. Low energy consumption and low propagation delay are the most important and common
objectives. The influence of \( \varphi_1 \) and \( \varphi_2 \) on the average energy consumption and average delay will be observed and analyzed in this simulation.

There are three observations from Figure 6: (a) when \( \varphi_2 \) is set, the increase in \( \varphi_1 \) generally leads to the reduction in average energy consumption, and reduction is significantly weakened if \( \varphi_1 \) is large enough; (b) when \( \varphi_1 (\varphi_1 \neq 0) \) is set, the increase in \( \varphi_2 \) gives rise to a slight increase in average energy consumption because the QoS model is more concerned about propagation delay with a varying \( \varphi_2 \); (c) at \( \varphi_1 = 0 \), the plot has irregular fluctuations, and \( \varphi_2 \) consistently increases due to the randomness of topology (objective (iii)). An increase in \( \varphi_2 \) results in the contraction of the average delay of a single hop, and conversely, an increase in \( \varphi_1 \) causes the extension of the average delay of a single hop (Figure 7).

7.5. Average Path Bandwidth. Set \( \varphi_3 = 0.1 \) and \( \varphi_1 = \varphi_2 = \varphi_4 = 0 \). When \( \chi \) is assigned as 5, 7, and 10, respectively, the average path bandwidth exhibits the three plots shown in Figure 8. A higher average path bandwidth will be obtained with higher values of \( \chi \). This is because an increase in \( \chi \) implies enlargement of the set optional strategies, and better strategies may be selected for the nodes. The average path bandwidth has irregular fluctuation as \( N \) increases when \( \chi \) is determined. Although lower-ranked strategies can be selected while more nodes are deployed, increasing path hops is possible. Therefore, the average path bandwidth is not affected by \( N \). Moreover, from Figure 9, when \( \varphi_3 = 0.1 \) and \( \varphi_1 = \varphi_2 = \varphi_4 = 0 \), the average path bandwidth obtained by SAA is higher than those by other algorithms, which did not take transmission bandwidth into account.
7.6. Average Path Transmission Success Ratio. Set $\varphi_4 = 0.8$ and $\varphi_1 = \varphi_2 = \varphi_3 = 0$. The curved surface peak is nearly $0.89$ ($\chi = 10$, $N = 2700$), as shown in Figure 10. At a fixed $\chi$, the variation in average path transmission success is irregular as $N$ increases; the reason for this is similar to that in Simulation E. The phenomenon suggests that SAA is scalable with respect to the number of nodes. As shown in Figure 11, transmission success ratio of SAA is significantly higher than those of FiYG, LMST, and EBC, and the SAA plot fluctuates obviously with the increase of $N$. This is because dense nodes deployment will result in extension of practical strategy space, which will improve transmission success ratio probably. However, meanwhile an increase of hops number on paths giving rise to the reduction of transmission success ratio will be caused as well.

In summary, (a) the proposed algorithm SAA efficiently improves performance in terms of energy consumption, propagation delay, bandwidth, and transmission success rate while meeting both full coverage and global connectivity; (b) the simulation results indicate average energy consumption and UWSN lifetime: the average delay is optimized while $N$ increases, whereas the average path bandwidth and average path transmission success ratios are independent of $N$. Therefore, SAA possesses scalability with respect to the number of nodes; (c) according to different multiobjectives of UWSN applications, SAA shows favorable performance at properly set parameters.

8. Conclusions

Aiming at the particularity of water medium and underwater acoustic communication, the QoS topology control problem was studied in this paper, and a distributed SAA was designed accordingly. SAA can exhibit outstanding performance in every typical objective. However, the UWSN model in this paper is idealistic, that is, it prohibits node mobility, and delays from calculation, energy consumption by receiving messages are neglected. Furthermore, the communication range and sensing range of nodes are irregular rather than spheres. Addressing QoS topology control in more real environments or scenarios is suggested for further study.

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