Efficient Surface-level Gateway Deployment Using Underwater Sensing And Processing Networks

Hesham Alhumyani, Reda Ammar, Ayman Alharbi, Sherif Tolba
{Hesham, Reda, Ayman, sat09003}@engr.uconn.edu
Computer Science and Engineering
University of Connecticut, Storrs, CT 06269

***Abstract*—Underwater sensor networks (UWSN) have two major challenges: limited bandwidth and high propagation delay. In-network processing can improve the performance of UWSN data flow in the network, leading to better channel utilization. In order to do this, processing nodes have to be deployed to perform local processing, such as compression, mining, and feature extraction on the collected data. In this paper, we first develop an optimization framework based on Integer Linear Programming (ILP) for processing node deployment. We then solve the problems of processing and surface-level gateway node deployment and investigate their trade-offs. The advantage of processing node deployment on end-to-end delay and network lifetime is highlighted. Our results show that deploying processing nodes can minimize the number of surface-level gateways in addition to improving the performance of the network. Simulations are used to validate our work and show the advantages of the proposed architecture.**

***Index Terms*—Processing node, Surface-level gateways, Underwater sensing and processing networks.**

I. Introduction

Underwater wireless sensor networks (UWSN) have been evolving for the last decade. They have many potential applications, including seismic monitoring, equipment monitoring, leak detection, and military applications [1] [2]. However, due to the harsh underwater environment, UWSN face many challenges [3]. They suffer from limited bandwidth, which results in a high transmission delay and high-energy consumption. Communication in UWSN is very challenging compared to the terrestrial wireless sensor networks, and electromagnetic waves cannot be used due to the quick absorption in water. Therefore, UWSN use acoustic waves for communication, which are five orders of magnitude slower than electromagnetic waves due to the low propagation speed of sound. This can result in a high propagation delay that would greatly increase the end-to-end delay. These factors affect the performance of UWSN and make the transferring of large data sizes more challenging.

Underwater sensor nodes are battery operated and, because of the intrinsic condition of the deployment sites, it is usually hard to replace or recharge their batteries. Furthermore, underwater modems are energy-hungry devices and in order to transmit a large volume of data they require much more energy. Thus, power consumption is a major performance metric to be considered. In general, in-network processing, such as eliminating invaluable bits and aggregating raw data, can reduce energy consumption and improve sensor network lifetime significantly. Also, one of the main sources for end-to-end delay is the waiting time to share medium on each node. Therefore, it is reasonable to exploit this waiting time to perform local processing on the collected data during the time that the link is unavailable. As a result, only the required information is transmitted and there is no need to transmit the whole data volume. Accordingly, this leads to a minimum data size, efficient bandwidth utilization, and performance enhancement. Conventional underwater sensor nodes are limited to data sensing, transmitting, and forwarding and have limited processing capability. Therefore, we assume that a processing node has a higher power capability, larger memory size, and a higher computational capability. Since this type of node has more features compared to the conventional underwater sensor nodes, its cost is also higher. Hence, there is a tradeoff between the number of processing nodes and the application requirement.

Deploying multiple surface-level gateways can alleviate the problem of high propagation delay [4]. Unlike single sink networks, data can be transmitted to the nearest sink instead of using long underwater paths to reach the unique one. Moreover, surface-level gateways are radio-capable devices and hence they forward data using electromagnetic waves to the control station with smaller energy and negligible time compared with the time required using acoustic waves [5]. However, underwater surface gateways tend to be more powerful and expensive devices compared to the conventional underwater sensors. Multiple surface-level gateways can be vulnerable to security attacks since they work as data aggregators and provide critical services such as localization and synchronization information. If these nodes are damaged or compromised, then the whole network or part of it (if multiple-surface gateways are used) would be ruined and hence, the more surface-level gateway nodes, the more security threats UWSN will undertake [6]. Since they are expensive and vulnerable to physical attacks, the objective is always to minimize their number while matching constraints on delay, energy efficiency, and network quality [7] [8] [9].

The main contributions of this paper are:

(a) To study the problem of processing node deployment on a grid of candidate sensor nodes. The focus is to optimize the cost of processing node deployment by finding the optimal locations and the minimum number required to achieve a given

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design objective.

(b)Investigating the effect of processing node deployment on the multiple surface-level gateways deployment in [4] and study how the number of surface-level gateways could be minimized.

The rest of this paper is organized as follows. In Section II, we briefly discuss several closely related studies. In Section III, the network model, assumptions, and optimization problem formulation regarding the processing nodes deployment problem are presented and justified. In Section IV, the effect of processing nodes deployment on the surface-level gateways problem is analyzed. In Section V, simulation study and results are shown. Finally, in Section VI, conclusions are drawn and some future work is presented.

II. Related work

There has been a growing interest in acquiring oceanographic, biological, and biophysical data in order to study how different aspects of human life can be improved. Endeavors such as navigation, sea current monitoring, weather forecasting, and oil leakage detection depend on accurately gathering large amounts of data across various temporal and spatial scales. Such application requires the collection of big and accurate data across various temporal and spatial scales. The current approach for large data acquisition involves recovering the collected data at the end of the mission using electromagnetic waves and having Autonomous Underwater Vehicles (AUV) periodically visit the nodes [10]. However, this strategy has many drawbacks: first, AUV need accurate optical alignment between sender and receiver. Second, in this case data may remain uncollected for days, weeks, or months and postponing data analysis and processing until recovery time. Third, there is no guarantee that underwater sensor nodes will be alive during the time of the mission and hence the whole recorded data may be lost. Our previous work [11] addressed these problems by introducing an underwater computing network architecture called underwater sensing and processing nodes (USPN). USPN is an architecture that aims to adopt efficient data processing algorithms to be performed underwater (in-network processing). This leads to minimum data size, efficient bandwidth utilization, and performance enhancement. Subsequently, we developed efficient pipeline architecture for underwater big data analytics [12] . Considering more costly and complex data processing algorithms, we proposed different architectures that aim to perform pipeline data processing and transmission to make the real time monitoring more feasible using acoustic waves. However, both [11] and [12] are limited to linear (chain) topology only. In this paper, we consider deploying processing nodes on a grid topology to study the improvement in the end-to-end delay and average network lifetime.

III. Underwater processing nodes deployment strategy

The processing nodes deployment is modeled as a 3-D graph optimization problem. The nodes of the graph represent the surface gateways and the underwater sensors. The underwater sensors act as candidate positions for underwater processing sensors. Fig.1 shows our network architecture consisting of different types of nodes: regular sensor node, relay node, processing sensor node, and surface-level gateway node. The problem is to choose a subset of pre-existing candidate underwater sensors positions to deploy the underwater processing nodes and to satisfy a set of constraints: Per-node flow conservation, end-to-end flow conservation, deployment cost constraints (number of processing units), and data quality constraints. Static underwater deployment is considered in this work. We assume that data generated by each node and all the acoustic transceivers are homogeneous. Also, surface-level gateways work as a virtual sink; therefore, we assumed that packets delivered to any one of them are delivered to the control station. Furthermore, to simplify the problem, a simple interference model is used where a node cannot transmit while it is receiving from a node within its communication range.

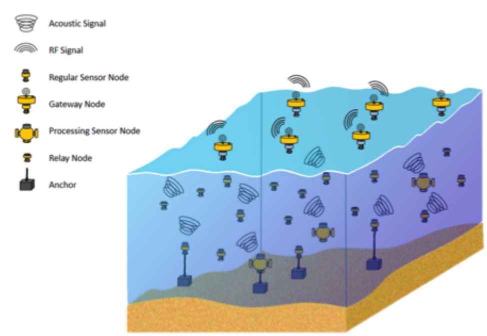

Fig. 1. An illustration of the network architecture

1. Definitions:

1.1. Nodes and edges: The network is modeled as a graph $G = \{V, E\}$where V represents the set of all nodes in the network and E is the set of all communication links between nodes. Let U be the set of all underwater sensor nodes,T be the set of surface gateway nodes, P be the set of processing nodes where $P \subset U$, $pi \in U, \forall i = 1, 2.., K$ $i.e. V = U \cup T$. Let $I(u)$ be the set of nodes within the communication range of node u, $i.e. I(u) = \{v : \ v \in U, u \neq v; \ d(u, v) < C\}$, where $d(u, v)$ denotes the Euclidean distance between u and v, and C is the communication range. E_{out} and E_{in} are the outgoing and incoming links $i.e. E_{out}(v) = \sum_{w_i \in I(v)} e(v, w_i)$ and $E_{in}(v) = \sum_{w_i \in I(v)} e(w_i, v)$ where, $e(v, w)$ represent the link between node v and w such that $v \in V, w \in I(v)$.

1.2 Data flow and traffic generation: Let $f(e)$ be the total data flow on edge e in (packets/s). Each node is associated with a local data generation rate (traffic load) $i.e.$ $g(v)$ at $v \in V$. We define G to be the total data generation rate for the whole network $i.e.$ $G = \sum_{v_i \in V} g(v_i)$.

1.3 Processing ratio: we define the processing ratio α to be the percentage of the original data volume that has been reduced after processing i.e.

$$\alpha = \begin{cases} x, & 0.1 < x < 0.9 \text{ if the node processed data} \\ 1 & \text{otherwise} \end{cases}$$

2. Constraints:

2.1 Per-Node Flow Conservation: Since we are performing local processing on the generated data, the flow conservation for underwater sensor nodes can be defined to be the sum of the flows leaving a node is less than or equal to the sum of the flows entering that node plus the local data generation rate.

$$\sum_{e_o \in E_{out}(v)} f(e_o) \leq \sum_{e_i \in E_{in}(v)} f(e_i) + \alpha g_v \quad (1)$$

2.2 End-to-End Flow Conservation: Data generated by any source can be received at any surface gateways. Therefore, the flow conservation implies that the total data generation rate must be less than or equal to the total received data rate to all surface node sensors.

$$\sum_{t_j \in T} \sum_{e_i \in E_{in}(v)} f(e_i) \leq G \quad (2)$$

2.3 Number of processing nodes: Processing node is more expensive compared to the regular underwater sensor node and hence according to the available budget, the number of processing nodes is limited to K nodes.

$$\sum_{v_i \in P} v_i \leq K \quad (3)$$

2.4 Data quality constraint: Due to some underwater environmental conditions, different zones of the network have some constraints on the quality of data. For instance, in the case of images the amount of light reaching the sensor is crucial and might affect image quality. So each candidate underwater sensor node has Qi constraint.

$$\alpha_i \leq Q_i \quad (4)$$

2.5 Interference Constraints: In this paper, we assume a simple interference model, in which a node cannot send and receive at the same time. Therefore, the total incoming and outgoing flow of a certain node cannot exceed the communication link capacity B. Hence, the interference constraint is written as follow:

$$\sum_{e_o \in E_{out}(v)} f(e_o) + \sum_{e_i \in E_{in}(v)} f(e_i) \leq B \quad (5)$$

3. Objective functions:

The main goal of the optimization problem is to find the optimal processing nodes locations using K processing nodes according to minimizing the expected end-to-end delay and maximizing the expected network lifetime.

3.1 Minimizing expected end-to-end delay: We aim to minimize the expected source-to-destination delay for all packets. The delay for a packet is the sum of per-hop delay on each edge along the path from the source of data to the surface gateway. The per-hop delay τ for each edge e is defined to be the sum of transmission delay, propagation delay, processing delay and queuing delay. Therefore, the per-hop delay can be written as:

$$\tau(e) = \tau_{tr}(e) + \tau_p(e) + \tau_q(e) + \tau_{proc}(e) \quad (6)$$

$i.e. \quad \tau_p(e) = \frac{d}{\rho}$, and $\tau_{tr}(e) = \frac{L}{B}$

Where τ_{tr} is the transmission delay, which is equal to the packet length (L) in bits divided by channel bandwidth (B) in bits per seconds. τ_p represents the propagation delay which is the distance (d) in edge e divided by the acoustic propagation speed in water. Therefore, the objective function is to minimize the expected end-to-end delay for all packets:

$$\text{minimize } E[\tau(e)] \quad (7)$$

Where $E[\tau(e)] = \frac{1}{G} \sum_{e \in E} (f(e).\tau(e))$

3.2 Maximizing expected network lifetime: We define the expected network lifetime as the expected working time that can be achieved by all underwater sensor nodes until any of them dies. In order to present the objective function, we first need to describe the energy model used in this work.

- Energy model:

The signal to noise ratio (SNR) is characterized by the passive sonar equation [13]:

$$SNR = SL - TL - NL + DI \quad (8)$$

Where SL is the source level, TL is the Transmission Loss, NL is the noise level, and DI is the Directivity Index. The noise level NL results from different factors such as: water turbulence, shipping traffic, volcanic activity, wind level and biological noise. The directivity index DI is set to be zero since we assume omnidirectional hydrophones. The transmission loss TL includes both sound spreading loss and attenuation. The sound spreading loss pattern is of two types: cylindrical spreading for shallow water, and spherical spreading for deep water. Hence, the transmission loss equation presented by [14] is written as:

$$TL = y \ logd + \beta d \times 10^{-3} \quad (9)$$

where y is the spreading factor which is usually set to 10 for cylindrical spreading and 20 for spherical spreading. In practical underwater setting, the sound-spreading pattern is a hybrid of spherical and cylindrical spreading [15], therefore, y is set to 15 in our case. d is the distance between the sender and receiver. β is the absorption coefficient expressed using Thorp's formula that returns $B(f)$ in dB/km for f in kHz as:

$$\beta(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + \frac{2.75 f^2}{1000+f^2} + 0.003 \quad (10)$$

By solving the above equations, SL can be obtained to determine the transmission power using the following equation [13]:

$$P_{tr} = 2\pi \times H \times 10^{\frac{SL}{10}} \times 0.67 \times 10^{-18} \quad (11)$$

Therefore the power consumed per packet between source u and destination v on edge e is written as follow:

$$P^u(e) = P^u_{tr}(e) + P^u_{rc}(e) + P^u_{proc}(e) \tag{12}$$

Where $P^u_{rc}(e)$ is the reception power, $P^u_{proc}(e)$ is the processing power. Hence the expected power consumption for all packets is expressed as follow:

$$E[P(e)] = \frac{1}{G}\sum_{e\in E}(f(e).P(e)) \tag{13}$$

Next, from the lifetime model presented in [16], we need to determine the time that a node's transceiver is active during one update period. Since we have assumed homogenous data volumes, the active time T is written as follow:

$$T_{active-one-update} = \frac{D_{volume}}{B} \tag{14}$$

in seconds. Where D_{volume} is the whole data volume that needs to be transmitted from each source node during one update period. The total active time of a transceiver is defined to be the ratio of the expected available energy to the expected power consumed in one frame:

$$T_{active} = \frac{E[E_{initial}]}{E[P(e)]} \tag{15}$$

in hours. Therefore the objective function is to maximize the network lifetime:

$$\text{Max } T_{lifetime} \tag{16}$$

$$i.e. \qquad T_{lifetime} = \frac{T_{active-one-update}}{T_{active}} \times \frac{R}{24}$$

in days where R is the update period in seconds.

IV. Efficient Surface-level Gateway Deployment

In this section we study the effect of underwater processing node deployment on the multi-surface gateways presented in [4]. Given the network with an optimal processing node deployment, we need to find the minimum number of gateways that can be used while preserving the same performance or gaining a better performance compared to the non-processing network. Moreover, since the data packets received by the surface gateways have been reduced, there is a need for the surface gateways to be redeployed in order to assure the optimal deployment with the updated network traffic. Therefore, reducing the data flow in a certain path can result in allowing connection of the last node to a farther surface gateway rather than the nearest one. Thus, a reduction in the number of surface-level gateways is obtained and hence the cost of the network is minimized. Algorithm 1 describes the procedure of finding the minimum number of surface-level gateways and their locations:

Algorithm 1 find the minimum Number of surface-level Gateways and their locations

begin
  Give an id number to each underwater node 1, 2,$\cdots$,n.
  Given k available surface-level gateways.
  Start the surface-level Gateways deployment procesdure.
  Solve the processing node deployment problem.
  Gateways redeployment
  $d_0 = calculateDelay$
  $p_0 = calculatePower$
  $cost_0 = d_0 \times p_0$
  do
    k--;
    if $k \leq 1$ **then**
      $break$;
    end if
    Gateways redeployment
    $d_i = calculateDelay$
    $p_i = calculatePower$
    $cost_i = d_i \times p_i$
    $Performance\ gain = \frac{cost_{i-1}}{cost_i}$
  while $(Performance\ gain \geq 1)$
end

V. Simulation study

A. Simulation settings: To evaluate our work, we use simulation to verify the need of the processing nodes and its improvement in the surface-level gateways problem [4]. Throughout the experiment we fixed some parameters in order to test and evaluate the work. Table 1 lists the values of these parameters:

TABLE I
LISTS OF FIXED PARAMETERS

Parameter	Quantity
Bit Rate (B)	10kbps
Frequency (f)	20 kHz
Packet Size (L)	400 bit
Data generation rate (g)	2.5 packets/sec
Signal-To-Noise-Ratio (SNR)	15 dB
Spreading factor (y)	15
Initial energy (E_{intial})	1e4 joules
Processing Node Initial Energy ($\bar{E}_{intial}$)	1e6 joules
Transmission range	150 m
Update period (R)	1500 seconds

B. Results and analysis: In all simulation scenarios, 49 nodes are distributed randomly in a square area of 600m x 600m with a depth of 100 m. 19 surface sinks are deployed on the water surface and have been chosen according to the surface-level gateway optimization problem [4] with a mesh of 5 x 5 candidate locations. We considered LZW compression algorithm [17] [11] as the performed processing technique. The processing time and power for compression are negligible compared to the transmission. However, when we consider other processing types, more processing time and power are needed.

In order to study the effect of adding processing nodes into the network, we evaluate the performance by taking into consideration different performance metrics such as delay gain, power gain, and monetary cost gain. Therefore, the performance gain formula can be rewritten as:

$$Performance\ gain = delay\ gain \times power\ gain \times monetary\ cost\ gain \quad (17)$$

$$= \frac{delay_{i-1}}{delay_i} \times \frac{power_{i-1}}{power_i} \times \frac{mCost_{i-1}}{mCost_i}$$

Where $delay_0$, $power_0$, and $mCost_0$ is the delay, power, and monetary cost respectively of the network before adding any processing node. Figure 2 shows the effect of adding processing nodes according to the performance gain expression (17). When the number of allowed processing nodes increases, the network performance is expected to improve. To verify this, we vary the number of allowed processing nodes from 1 to 49 nodes and solve the optimization problem. As clearly seen from Figure 2, an increase in the number of processing nodes can dramatically enhance the performance gain. However, after a certain number (a threshold) of processing nodes, additional processing nodes have no positive effect on the performance of the network. This is because that before the threshold is reached, the improvement in the delay gain and power gain outweighs the increase in the monetary cost. Moreover, when the threshold is reached, the increase in the monetary cost outweighs the improvement in the delay gain and power gain. Therefore, any further addition of processing nodes becomes costly.

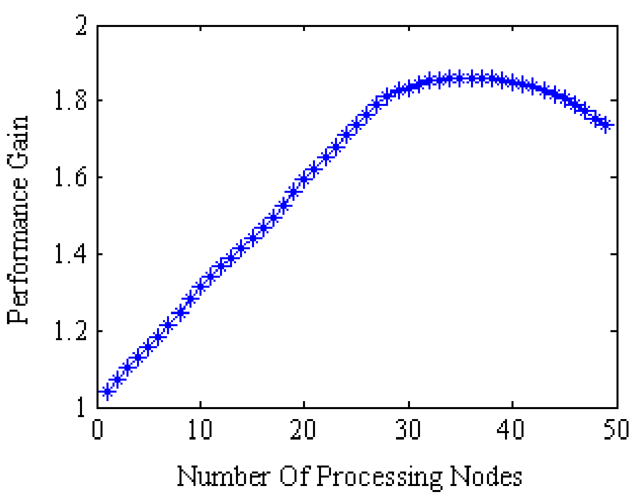

Fig. 2. Processing nodes vs Performance gain

Processing node deployment plays a major role in maximizing the network lifetime. Performing in-network processing results in reducing the amount of data to be transmitted and hence an energy efficient network is obtained. Furthermore, in case of collisions and packets lost there is a need for retransmission, so carrying less data would greatly improve the performance. Fig.3 represents how the expected network lifetime is improved with processing node deployment. By varying the number of processing nodes from 1 to 49 and solving the optimization problem for the objective of maximizing the expected network lifetime, the obtained result shows that an increase in the number of processing nodes can greatly results in increasing in the expected network lifetime. Due to the reduction ratio constraint (4) as well as the underwater deployment, it is clearly seen that after a certain point, the expected network lifetime is slightly improving. Also, we compare the expected network lifetime before and after processing to show the impact of deploying these types of nodes.

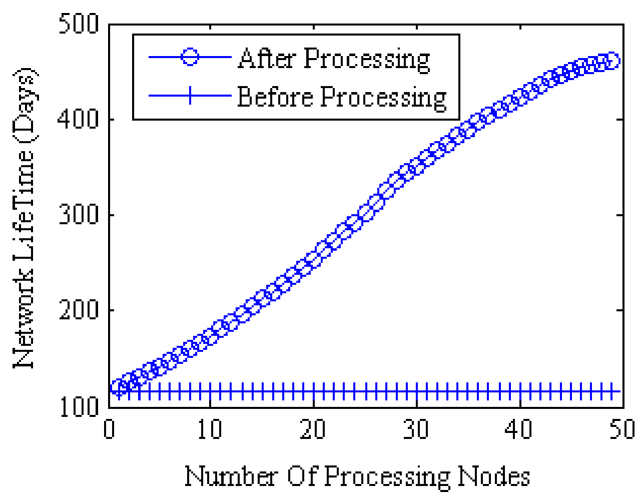

Fig. 3. Effect of processing nodes deployment on network lifetime

To evaluate our work, we studied the effect of processing nodes to the surface-level gateways deployment presented by [5]. As depicted from Fig.4, the expected end-to-end delay is decreased when more processing nodes are deployed. Furthermore, the end-to-end delay is further improved with more surface-level gateways deployed on the site. However, as we discussed earlier, the surface-level gateways are costly and the target is to reduce their number. Therefore, we jointly solved the processing node optimization problem with the surface-level gateways optimization problem in [5] to show the effect of the processing node deployment in reducing the number of gateways. Fig.5 reveals that the more processing nodes, the fewer gateways can be obtained with a better or equal performance. For example, Fig. 5 shows that the number of surface-level gateways can be reduced from 19 to 8 by using only ten processing nodes. However, after a certain number, (in our case 17 processing nodes from Fig.5), adding more processing node then would be expensive for the purpose of reducing the surface-level gateways as the network needs a minimum number of gateways to maintain its performance gain.

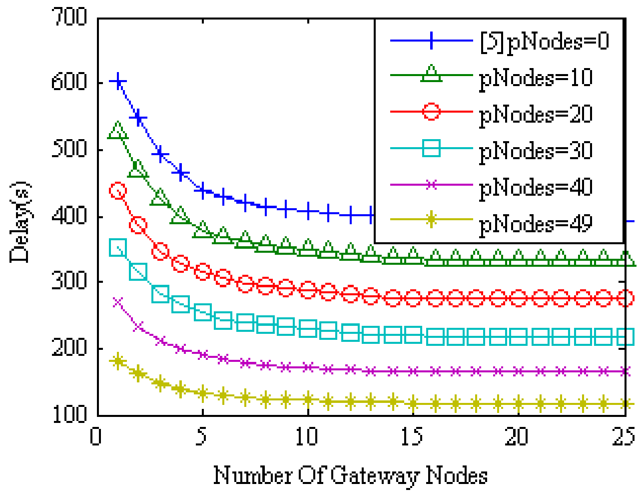

Fig. 4. Average delay improvment vs Surface-level gateways with processing nodes deployment

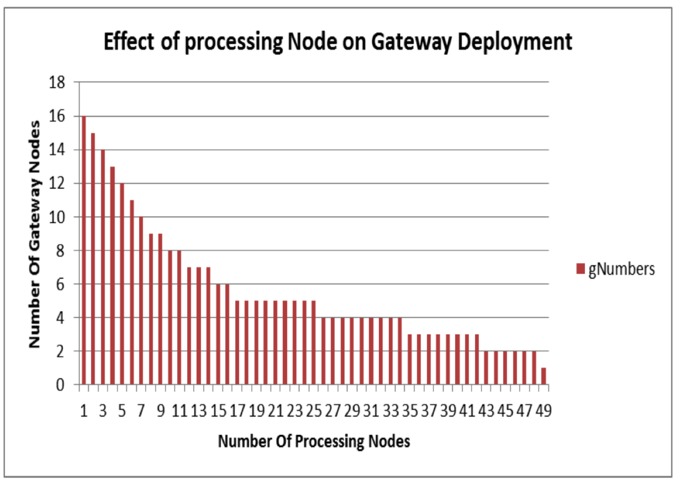

Fig. 5. Processing nodes vs Surface-level gateway nodes

VI. Conclusion and Future Work

In-network processing represented by the underwater sensing and processing network will be the new generation of UWSN. Obtaining the required information from raw data in real time is more efficient than carrying the whole data to data centers. It then requires more time and high performance computing in order to perform the analysis. In this paper, we developed and presented an optimization problem for processing nodes deployment. Then, we investigated the impact on the surface-level gateways optimization problem [5] with processing node deployment. Simulation confirms the benefit of the processing node deployment on improving the network performance such as expected end-to-end delay and expected network lifetime in reducing the number of gateways. It has been shown that deploying processing nodes plays a significant role in reducing the surface-level gateways. This work paves the way for more in-network processing in the UWSN field. Finally, in future work, we are planning to develop algorithms for processing node placement which lead to a better solution for the optimization problem that can results in reducing the size of the problem.

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