Received December 18, 2016, accepted January 20, 2017, date of publication January 27, 2017, date of current version August 22, 2017.
*Digital Object Identifier 10.1109/ACCESS.2017.2660767*

# Balanced Load Distribution With Energy Hole Avoidance in Underwater WSNs

**IRFAN AZAM[1], NADEEM JAVAID[1], (Senior Member, IEEE), ASHFAQ AHMAD[1], (Student Member, IEEE), WADOOD ABDUL[2], (Member, IEEE), AHMAD ALMOGREN[2], AND ATIF ALAMRI[2], (Member, IEEE),**
[1]COMSATS Institute of Information Technology, Islamabad 44000, Pakistan
[2]Research Chair of Pervasive and Mobile Computing, College of Computer and Information Sciences, King Saud University, Riyadh 11633, Saudi Arabia
Corresponding author: Nadeem Javaid (nadeemjavaidqau@gmail.com)

This work was supported by King Saud University, through Vice Deanship of Research Chairs.

**ABSTRACT** Due to limited energy resources, energy balancing becomes an appealing requirement/challenge in Underwater Wireless Sensor Networks (UWSNs). In this paper, we present a Balanced Load Distribution (BLOAD) scheme to avoid energy holes created due to unbalanced energy consumption in UWSNs. Our proposed scheme prolongs the stability period and lifetime of the UWSNs. In BLOAD scheme, data (generated plus received) of underwater sensor nodes is divided into fractions. The transmission range of each sensor node is logically adjusted for evenly distributing the data fractions among the next hop neighbor nodes. Another distinct feature of BLOAD scheme is that each sensor node in the network sends a fraction of data directly to the sink by adjusting its transmission range and continuously reports data to the sink till its death even if an energy hole is created in its next hop region. We implement the BLOAD scheme, by varying the fractions of data using adjustable transmission ranges in homogeneous and heterogeneous simulation environments. Simulation results show that the BLOAD scheme outperforms the selected existing schemes in terms of stability period and network lifetime.

**INDEX TERMS** Underwater wireless sensor networks, energy hole, balance load distribution, weight, energy balancing, stability.

## I. INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) consist of sensor nodes which gather data from underwater environment and periodically report it to the sink. Our research community is getting interest in UWSNs during the last 15 years [1]. UWSNs are being important due to demanding oceanic applications, i.e., ocean surveillance for defense strategies, underwater explorations, tsunami and earthquake monitoring, pollution monitoring, etc. Designing, manufacturing, and deploying the UWSNs are difficult tasks and underwater sensor nodes are costly [2]. Moreover, it is challenging to design a protocol for UWSNs by considering the limited parameters for underwater communication.

The protocols designed for terrestrial Wireless Sensor Networks (WSNs) cannot work well for UWSNs because of different implementation environments. Radio and optical signals are mostly affected by absorption loss in underwater environments and cannot be used for underwater communications. Acoustic signals are used as transmission media in UWSNs instead of radio signals, which is quite challenging due to many reasons [1]–[3].

- Bandwidth of acoustic signals is severely limited than radio signals.
- Speed of acoustic signals is 1500 m/s while radio signals move with a speed of $3 \times 10^8$ m/s.
- High Bit Error Rate (BER) due to multipath fading, path loss, transmission loss, etc.

Sensor nodes in UWSNs report generated data as well as relay received data of previous hop sensor nodes to the sink. Nodes near the sink forward more data as compared to the nodes farther from the sink and energy consumption of the nodes near the sink is relatively higher than other nodes of the network. An energy hole problem near the sink due to early death of nodes is called energy sink hole problem. Direct data transmission is an easy way of reporting data to the sink if the transmission range of each sensor node is large enough to reach the sink. On the other hand, if all nodes directly communicate with the sink then the nodes farther from the sink quickly drain out their energy.

In Nominal Range Forwarding (NRF) scheme [4], sensor nodes send data (generated and received) to the sink using one-hop transmission range, i.e., $\{r\}$, which results in maximum load at one-hop neighbors of the sink. Balanced Routing (BR) scheme [5] minimizes the load at one-hop neighbors of the sink by dividing data at each node into two fractions; small and large. The small fraction of data is forwarded to the next one-hop neighbors using the one-hop transmission range, i.e., $\{r\}$ and large fraction of data is forwarded to the next, two-hop neighbors using two-hop transmission range, i.e., $\{2r\}$. However, the load at two-hop away neighbors of the sink increases because all sensor nodes of that corona 2 become one-hop neighbors of the sink using the transmission range $\{2r\}$, which leads to unbalanced load and high energy consumption at corona 2. When two-hop neighbors of the sink die, the total data traffic at corona 3 and corona 4 increases, due to which data load received by corona 1 from corona 3 using transmission range $\{2r\}$ also increases, which leads to energy hole. Thus, balanced data load distribution is needed at both one-hop and two-hop neighbors of the sink along with overall load balancing of the network to achieve balanced energy consumption in the underwater network to avoid the energy hole problem for maximum network lifetime.

In this study (an extension of [6]), we target both one-hop and two-hop away neighbor nodes of the sink in corona 1 and corona 2 because in continuous monitoring applications, the maximum data is forwarded by these neighbor nodes of the sink. In short, we identify that the existing schemes unevenly distribute the load among the sensor nodes which is the major reason for the energy hole problem to occur. To tackle the problem discussed above, we propose the BLOAD scheme. In BLOAD, data at each node is divided into three fractions; small, medium and large. These fractions are forwarded using multihop transmission and direct transmission to the sink. In a mixed routing technique [7]–[9] each sensor node uses both a hop-by-hop transmission and direct transmission to achieve a balanced energy consumption through a balanced distribution of the total data traffic for maximum stability and lifetime of the network. In BLOAD, a mixed routing technique is used to balance the energy consumption of each sensor node of the network in order to prolong the stability period and network lifetime of UWSNs which are specifically designed for time critical and continuous monitoring applications. We consider sensor nodes which adjust their transmission power level according to the transmission distance and each node uses variable transmission ranges i.e., $\{r, 2r, dtx\}$. We balance the energy consumption of all sensor nodes of the network by sending some fraction of data directly to the sink using a direct transmission range, i.e., $\{dtx\}$ and some fraction of data hop-by-hop using hop-by-hop transmission ranges, i.e., $\{r, 2r\}$. All sensor nodes of the network act as one-hop away neighbors of the sink because of using a direct transmission range $\{dtx\}$. Thus, sensor nodes closest to the sink are relieved of relaying data, which avoids the energy sink hole problem. Similar to the BR scheme, each sensor node calculates the appropriate load weight for sending fractions of data using transmission ranges $\{r, 2r, dtx\}$ to evenly distribute the energy consumption among all sensor nodes. In [10], a mixed routing technique is used to deal with the unbalanced energy consumption problem in a random uniform deployed WSNs. However, we tackle the energy hole problem by considering a deterministic deployment of sensor nodes in a circular sensor field in UWSNs. The implementation of BR and BLOAD schemes is performed in heterogeneous and homogeneous environments to achieve a maximum stability period and energy balancing in the network. In the homogeneous environment, all sensor nodes in the network provides the same energy level. While, in the heterogeneous environment, the energy level of each node is different from other nodes in the network. Simulation results prove that the BLOAD scheme avoids the energy hole problem in UWSNs that are designed for time critical and continuous monitoring applications.

## II. RELATED WORK

In the past decade, many researchers have proposed routing protocols for energy balancing in WSNs, which are mostly unusable for UWSNs because of unique characteristics of underwater channels. The energy hole, which is formed due to unbalanced energy consumption is one of the key issues which has attracted the attention of many researchers. In this section, we discuss some existing protocols related to routing in UWSNs.

In Balanced Transmission Mechanism (BTM) [11], a hybrid routing mechanism is adopted and a two-dimensional network model is proposed. BTM balances the data load among all sensor nodes by dividing the energy of each sensor node into energy levels. When a node excessively consumes energy in multihop transmissions, it communicates directly with the sink. The disadvantage of BTM is high energy consumption for long distance transmissions when the network radius is increased. Also, the energy consumption in the coronas near and farther from the sink is not balanced.

The enhanced Efficient and Balanced Energy consumption Technique (EEBET) [12], overcomes the deficiencies in BTM. EEBET presents an Efficient and Balanced Energy consumption Technique (EBET) to avoid direct transmission at long distances for saving energy and calculates an optimum number of energy levels to enhance the network lifetime. The authors in EEBET protocol consider the problem of varying network radii for energy balancing. The issue of the energy sink hole at 1-hop and 2-hop neighbor coronas of the sink is not addressed by EEBET protocol.

In [13], authors propose Spherical Hole Repair Technique (SHORT) to repair coverage holes which are created due to energy holes. The technique has three phases: Knowledge Sharing Phase (KSP), Network Operation Phase (NOP) and Hole Repair Phase (HRP). In SHORT, nodes adjust their transmission power levels according to the location of the next hop node. SHORT takes the advantage of redundant overlapping of sensing ranges of nodes in dense UWSNs. However, due to coverage hole repairing time, SHORT is not suitable for delay sensitive applications.

**TABLE 1.** Comparison of UWSNs routing protocols.

| Protocol Deployment | Feature(s) | Parameter(s) Achieved | Parameter(s) Compromised |
|---|---|---|---|
| **BTM [20] Uniform** | Direct Transmission, Multihop Transmission, Balanced Energy Consumption | Energy Efficiency, Network Lifetime | High energy consumption for long distance transmission, Formation of transmission loops |
| **EEBET [21] Random Uniform** | Balanced Data Transmission | Energy Efficiency, Network Lifetime and Throughput | Performance decreases with increase of network radius |
| **SHORT [22] Random** | Coverage Hole Repair Technique | Network Lifetime and Throughput | End-to-end Delay |
| **GFCND [23] Random** | Guaranteed Full Connectivity Node Deployment Technique | Network Coverage and Connectivity rate | No Relationship of network topology with random node scattering |
| **EBH [29] Uniform** | Hybrid Data Transmission for Balanced Energy | Balanced Energy Consumption, Maximum Network Lifetime | Inefficient for Non-Linear and Dense Networks |
| **RDBF [25] Uniform** | Relative Distance Based Forwarding | Low end-to-end delay, Energy efficiency | Unbalanced load on nodes with minimum hop counts and less distance from the sink |
| **L2-ABF [26] Random Uniform** | Angle Based Flooding, Localization-free Routing | Energy Efficiency, Packet Delivery Ratio | End-to-end delay increases by increasing the number of layers |
| **MP-PSO [24] Random** | Localization-aware Routing | Energy Efficiency, Localization accuracy | High Computational Complexity |
| **HMR-LEACH [27] Random** | Hierarchical Multipath Routing Technique | Network Lifetime, Energy Efficiency | High End-to-end delay |

Peng *et al.* also address the coverage problem in UWSNs and propose a Guaranteed Full Connectivity Node Deployment (GFCND) and a Location Dispatch Based on Command Nodes (LDBCN) algorithms [14]. The GFCND algorithm, logically divides sensor nodes into two types: command nodes and connectivity nodes. A greedy iterative strategy is used to deploy coverage nodes for large coverage of the network and connectivity nodes are used for maximum network connectivity. The location adjustment of the common nodes with the help of the command nodes and sink nodes is accomplished by the LDBCN algorithm, to obtain the required network coverage rate and fully connected UWSNs. However, energy consumption is maximum to achieve full connectivity and high coverage.

Hanjiang *et al.* in [15], present Energy Balanced Hybrid (EBH) algorithm and Differential Initial Battery (DIB) assignment technique for balanced energy consumption of sensor nodes deployed in sparse linear networks. Maximum lifetime is achieved with EBH and DIB strategies in sparsely deployed UWSNs. However, the proposed strategies are inefficient for densely deployed UWSNs. These techniques are inefficient for non-linear networks.

In [16], authors propose a relative distance based forwarding (RDBF) scheme for energy efficient and minimum delay routing in UWSNs. In RDBF, an appropriate sensor node is selected as a forwarder on the basis of a fitness function. The sensor nodes selected as forwarders' are only involved in routing. The forwarders nodes are selected for routing because of minimum distance from the sink and minimum hop counts of the routing path. RDBF achieves low end-to-end delay and energy efficiency in the network. However, there is unbalanced load on nodes with minimum hop counts and less distance from the sink.

Ali *et al.* in [17], present Layer by layer Angle-Based Flooding (L2-ABF) routing protocol for UWSNs. Sensor nodes are deployed in the form of layers and each sensor node calculates its depth. L2-ABF is a localization-free routing protocol in which each sensor node forwards data to the sink according to the calculated forwarding angle. Sensor nodes forward data to the node which lies in its angle-based zone. L2-ABF achieves less energy consumption and high packet delivery ratio. However, end-to-end delay increases by increasing the number of layers.

Authors in [18], propose a localization technique based on Mobility Prediction and a Particle Swarm Optimization algorithm (MP-PSO) for UWSNs. Beacon nodes are deployed to find the location information of unknown nodes in the network. Velocity information of each beacon node is acquired with the help of which unknown nodes velocities are estimated and with the help of mobility prediction technique, the location of an unknown node is predicted.

In [19], authors present a Hierarchical Multi-path Routing-LEACH (HMR-LEACH) algorithm for UWSNs, which is based on the LEACH algorithm. They use multipath routing algorithm instead of one hop routing algorithm. HMR-LEACH, checks the energy and distance for selecting the transmission path while transmitting data to the sink and assigns a weight to each transmission path. Each transmission path has its own selection probability. The HMR-LEACH technique improves the network lifetime and balances the energy consumption at the cost of high end-to-end delay. Related work discussed above is summarized in Table. 1.

## III. THE BLOAD

Energy balancing is necessary to prolong the network lifetime in UWSNs. When the data load of each sensor node in the network is distributed in such a manner that minimum energy is utilized, then the energy of the network is balanced. In this section, we describe the BLOAD protocol in detail. Many authors have addressed the energy sink hole problem, mostly in WSNs, where each sensor node periodically reports data to the sink using a nominal transmission range $r$. They concluded that energy sink hole is unavoidable using a nominal transmission range $r$. Therefore, we study the work in which sensor nodes use an adjustable communication range and each sensor node adjusts its transmission power according to the transmission distance. We use a mixed routing scheme in the proposed protocol in which sensor nodes send data to the sink using a direct transmission range, i.e., $\{dtx\}$ as well as hop-by-hop transmission ranges, i.e., $\{r, 2r\}$ to evenly distribute the energy among all sensor nodes of the network. We tackle the energy hole problem in one of the most important classes of UWSN applications, i.e., continuous-monitoring applications, where all sensor nodes periodically forward the data (generated plus received) to the sink.

### A. SYSTEM MODEL

Mostly, in UWSNs, nodes' deployment is sparse because of high cost as compared to the terrestrial wireless sensor networks. Underwater sensor nodes are bottom anchored and a floating buoy is attached in order to keep the depth of all sensor nodes the same and sensor nodes can only move horizontally within certain limits. We exploit this characteristic of UWSNs for energy balancing and consider continuous-monitoring applications in which underwater sensor nodes are deterministically anchored at the bottom in shallow UWSN. The system under consideration is a circular monitoring area $A$ of radius $R$ such that the density of deployed nodes is $\rho$ [4], [5]. The network field is logically divided into circular regions of equal width $r$ called coronas as shown in Fig. 1. Each corona $C_i$ contains the same number of nodes and all sensor nodes in a corona $C_i$ are at equal distance from the sink. Sensor nodes of corona $C_i$ periodically report generated data plus received data from coronas $C_{i+1}, C_{i+2}$ to the sink by forwarding data to the next coronas $C_{i-1}, C_{i-2}$ located in the way to the sink. The traffic is distributed for balancing energy consumption as shown in Fig. 2. Each sensor node adjusts its transmission power level according to the transmission distance [20].

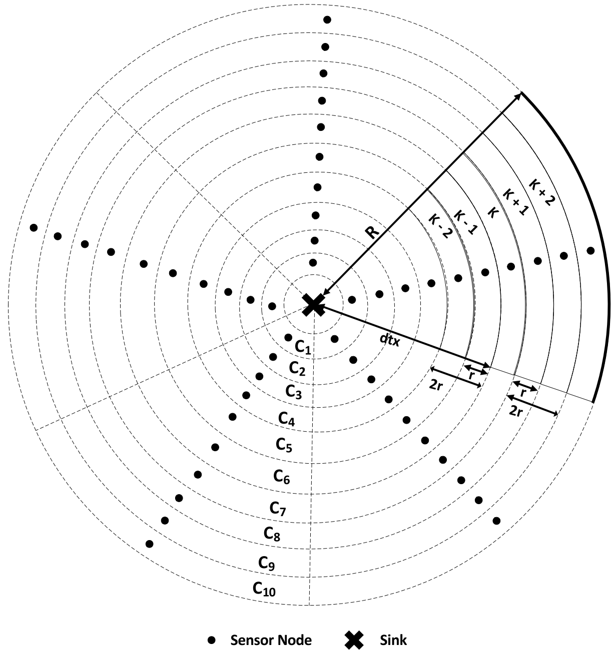



**FIGURE 1.** Network model of the BLOAD scheme.

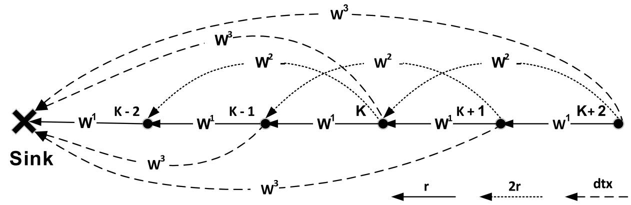



**FIGURE 2.** Network linear model of the BLOAD scheme.

### B. THE UNDERWATER CHANNEL MODEL

The transmission loss of an acoustic signal in underwater is given as follows [21]:

$$TL = k \cdot 10log(l) + l \cdot 10log(a(f)) \tag{1}$$

Where, $l$ is the distance in km, $f$ is the signal in frequency, $k$ is the spreading factor. $k = 2$ for spherical spreading, $k = 1$ for cylindrical spreading and $k = 1.5$ for practical spreading [22]. In eq. (1), $10loga(f)$ is the absorption coefficient (in $dB/Km$), which can be calculated using Thorp's formula [23]:

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

Eq. (2) is for frequencies above few hertz, for lower frequencies the following eq. (3) is used.

$$10log_{10}a(f) = 0.11\frac{f^2}{1+f^2} + 0.11f^2 + 0.002 \tag{3}$$

Attenuation in underwater acoustic channels is given in eq. (4) in $dB$ as follows:

$$A(l,f) = l^k a(f)^l \tag{4}$$

The SNR of an emitted signal of power $P$ is given in eq. (5).

$$SNR(l,f) = \frac{P/A(l,f)}{N(f)\Delta f} \tag{5}$$

where, $\Delta f$ is the received noise bandwidth.

Acoustic signals are effected by four types of noise in underwater communication: turbulence noise $N_t(f)$, waves noise $N_w(f)$, shipping noise $N_s(f)$ and thermal noise $N_{th}(f)$. The power spectral density of ambient noise is given in eq. (6) as

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{6}$$

We have used the central limit theorem for approximating the power spectral density of ambient noise in equation (6). Thus, irrespective of the individual parameters, the final model is approximated as Gaussian.

### C. ENERGY CONSUMPTION MODEL

The energy consumption of sensor nodes is due to transmission and reception and the total energy consumed by transmitting a packet of $P_n$ bits over a distance $l$ is given in eq. (7) as

$$E_{tx}(l) = P_T(l) \times \frac{P_n}{C_{3dB(l)}}. \tag{7}$$

The energy spent in receiving a packet of $P_n$ bits is given in eq. (8) as

$$E_{rx}(l) = P_{rx} \times \frac{P_n}{C_{3dB(l)}}, \tag{8}$$

where, $P_T$ is the transmitting power and $P_{rx}$ is the electronics power [5]. $C_{3dB}(l)$ is the capacity which is maximum allowed over bandwidth $B_{3dB}(l)$ as [22] and it can be calculated in eq. (9) as

$$C_{3dB}(l) = \int_{B_{3dB}(l)} log_2 \left(1 + \frac{P_{tx}(l)/B_{3dB}(l)}{A(l,f)N(f)}\right) df \tag{9}$$

The BLOAD scheme is designed for continuous monitoring applications where each sensor node continuously monitors the environment and periodically reports data (generated plus received) to the sink. The BLOAD scheme operates according to the following phases. In phase-I, the network is configured and all sensor nodes are informed about their location and distance from the sink. Then, the load weight is calculated for each corona nodes in phase-II. In phase-III, data is transmitted according to the calculated load weights. Each of the phase is discussed in detail in the upcoming subsections.

### D. NETWORK CONFIGURATION

Before transmitting data, information is exchanged through a periodic HELLO packet exchange mechanism. The HELLO packet contains information about each node's coordinates and residual energy status. If a node is introduced to the network, it simply shares the HELLO packet to inform its neighbors. On the other hand, if a node is discarded from the network, it ceases transmissions telling the other nodes not to communicate further with it.

### E. LOAD DISTRIBUTION PHASE

Before sensor nodes start transmission, the load weights $\{W^1, W^2, W^3\}$ are calculated for transmission ranges $\{r, 2r, dtx\}$. In this section we discuss in detail the packet load distribution for all coronas of the network. In NRF scheme, each node forwards data using transmission range $\{r\}$ and the packet load increases on the nodes near the sink because each node receives accumulative data of the previous hop node as shown in table 2. In the BR scheme, the load on the nodes

**TABLE 2.** Data load at each corona node in different time intervals during a data transmission in NRF Scheme.

| Time interval $t$ | Nodes $n$ in each corona | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $n_1$ | $n_2$ | $n_3$ | $n_4$ | $n_5$ | $n_6$ | $n_7$ | $n_8$ | $n_9$ | $n_{10}$ |
| $t_0$ | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_1$ | 0 | 20 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_2$ | 0 | 0 | 30 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_3$ | 0 | 0 | 0 | 40 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_4$ | 0 | 0 | 0 | 0 | 50 | 10 | 10 | 10 | 10 | 10 |
| $t_5$ | 0 | 0 | 0 | 0 | 0 | 60 | 10 | 10 | 10 | 10 |
| $t_6$ | 0 | 0 | 0 | 0 | 0 | 0 | 70 | 10 | 10 | 10 |
| $t_7$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 80 | 10 | 10 |
| $t_8$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 10 |
| $t_9$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |

**TABLE 3.** Data load at each corona node in different time intervals during a data transmission in BR scheme.

| Time interval $t$ | Nodes $n$ in each corona | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $n_1$ | $n_2$ | $n_3$ | $n_4$ | $n_5$ | $n_6$ | $n_7$ | $n_8$ | $n_9$ | $n_{10}$ |
| $t_0$ | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_1$ | 0 | 11 | 19 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_2$ | 0 | 0 | 20.43 | 19.57 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_3$ | 0 | 0 | 0 | 22.63 | 27.37 | 10 | 10 | 10 | 10 | 10 |
| $t_4$ | 0 | 0 | 0 | 0 | 31.44 | 28.56 | 10 | 10 | 10 | 10 |
| $t_5$ | 0 | 0 | 0 | 0 | 0 | 33.91 | 36.09 | 10 | 10 | 10 |
| $t_6$ | 0 | 0 | 0 | 0 | 0 | 0 | 44.57 | 35.43 | 10 | 10 |
| $t_7$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 41.67 | 48.33 | 10 |
| $t_8$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 62.92 | 37.08 |
| $t_9$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 38.34 |

near the sink is distributed by dividing the total data generated and received by a node into two fractions which are derived (table 6) for each corona for transmission of data at one-hop and two-hop neighbors using transmission ranges, i.e., $\{r, 2r\}$. In the BR scheme, these fractions of data are known as weights and the data load received according to these weights at each corona nodes is shown in table 3. Weights are fractions of the total data defined by each node to distribute data evenly on next hop sensor nodes. These weights are calculated for each corona by a numerically solved partial uniform energy depletion problem after formulating it as a constrained nonlinear optimization problem, which can be easily solved using '*fmincon*' function in the Matlab optimization toolbox [5]. We have used the load weights $\beta_1$ and $\beta_2$ of BR scheme and derived eq. (10), eq. (11) and eq. (13) to find weights $W^1, W^2$ and $W^3$ respectively for dividing the total data (generated plus received) into three fractions; small, medium and large. The division of total data into small, medium and large fractions using load weights $W^1$, $W^2$ and $W^3$ is shown in table 4.

$$W^1 = \beta_1 * \beta_2 \quad (10)$$
$$W^3 = (\beta_2)^2 \quad (11)$$
$$W^2 = 1 - \beta_2(\beta_1 + \beta_2) \quad (12)$$

where, $\beta_1 + \beta_2 = 1$

$$W^2 = 1 - \beta_2 \quad (13)$$

where, $\beta_1, \beta_2$ are load weights of the BR scheme. The sum of all load weights is given as

$$W^1 + W^2 + W^3 = 1 \quad \text{and } W^3 > W^2 > W^1.$$

**TABLE 4.** Data load at each corona node in different time intervals during a data transmission in BLOAD scheme.

| Time interval $t$ | Nodes $n$ in each corona | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $n_1$ | $n_2$ | $n_3$ | $n_4$ | $n_5$ | $n_6$ | $n_7$ | $n_8$ | $n_9$ | $n_{10}$ |
| $t_0$ | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_1$ | 0 | 10.9 | 11 | 18.1 | 10 | 10 | 10 | 10 | 10 | 10 |
| $t_2$ | 0 | 0 | 12.23 | 19.52 | 18.25 | 10 | 10 | 10 | 10 | 10 |
| $t_3$ | 0 | 0 | 0 | 21.08 | 20.08 | 18.84 | 10 | 10 | 10 | 10 |
| $t_4$ | 0 | 0 | 0 | 0 | 23.2 | 22.6 | 24.2 | 10 | 10 | 10 |
| $t_5$ | 0 | 0 | 0 | 0 | 0 | 25.9 | 28.1 | 26 | 10 | 10 |
| $t_6$ | 0 | 0 | 0 | 0 | 0 | 0 | 33 | 32.5 | 24.5 | 10 |
| $t_7$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 36.5 | 29.1 | 34.4 |
| $t_8$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37.4 | 47.2 |
| $t_9$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 48 |

**TABLE 5.** Possible combinations of two sets W and R.

| W | Comb:01 | | | Comb:02 | | | Comb:03 | | | Comb:04 | | | Comb:05 | | | Comb:06 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | R | | | R | | | R | | | R | | | R | | | R | | |
| | r | 2r | dtx | r | 2r | dtx | r | 2r | dtx | r | 2r | dtx | r | 2r | dtx | r | 2r | dtx |
| $W^1$ | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| $W^2$ | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| $W^3$ | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| **Possible combinations** | r 2r dtx | | | 2r r dtx | | | dtx r 2r | | | r dtx 2r | | | 2r dtx r | | | dtx 2r r | | |

**TABLE 6.** Packet load distribution of BR scheme [5].

| Corona | $\beta_1$ | $\beta_2$ |
|---|---|---|
| **Corona 1** | 1 | 0 |
| **Corona 2** | 0.02 | 0.98 |
| **Corona 3** | 0.35 | 0.65 |
| **Corona 4** | 0.14 | 0.86 |
| **Corona 5** | 0.25 | 0.75 |
| **Corona 6** | 0.17 | 0.83 |
| **Corona 7** | 0.18 | 0.82 |
| **Corona 8** | 0.15 | 0.85 |
| **Corona 9** | 0.13 | 0.87 |
| **Corona 10** | 0.1 | 0.9 |

We found that different combinations of the data load weights and transmission ranges are formed using eq. (14) below which are shown in table 5. In order to find an optimum solution, we find all the possible combinations of the data load weights and transmission ranges. We have two sets $W$ and $R$ as follows:

$$\text{where, } W = \{W^1, W^2, W^3\} \text{ and } R = \{r, 2r, dtx\}.$$

The total number of possible combinations can be calculated as follows:

$$Comb(W, R) = \frac{W!}{(W-R)!}. \tag{14}$$

In the BLOAD scheme, the data (generated plus received) by each node is distributed in such a way that the energy consumption at each corona nodes is balanced and stability of the network is prolonged. We assume that initially each sensor node of the first corona $C_1$ generates $D$ number of packets. The total data traffic of each sensor of $C_1$ is composed of only locally generated data $D$ thus, their data load weight $W_1^1(r)$ is equal to 1. By receiving the traffic of the second corona $C_2$, the data forwarding load on $C_1$ nodes becomes relatively high. We compute $W_2^1(r)$ and $W_2^2(2r)$ for corona $C_2$ such that $W_2^1(r) + W_2^2(2r) = 1$ and $W_2^2(2r) > W_2^1(r)$. When the data is received from the third corona $C_3$, the energy consumption of $C_1$, $C_2$ and $C_3$ is balanced using load weights $W_3^1$, $W_3^2$ and $W_3^3$.

### F. DATA TRANSMISSION PHASE

During data transmission phase, each corona transmits the total data generated plus received. Each corona has the data $D$ which is generated by nodes in that corona, the data $D_{i+1}$ received from one-hop neighbors with load weight $W_{i+1}^1$ and the data $D_{i+2}$ received from two-hop neighbors with weight $W_{i+2}^2$. The eq. (15) describes the total data (generated plus received) $D_{C_{i,t}}$ by corona $C_i$:

$$D_{C_{i,t}} = D + W_{i+1}^1 \cdot D_{i+1} + W_{i+2}^2 \cdot D_{i+2}, \quad \forall 1 \le i \le C-2, \tag{15}$$

where, $D$ is the average number of packets generated by each node in $C_i$ per unit of time.

Each node in a corona receives data from one-hop and two-hop neighbor nodes. The number of data packets received by $C_i$ from one-hop and two-hop neighbor nodes is given by

$$S_{C_{i,r}} = \sum_{k=1}^{n} W_{i+k}^1 \cdot D_{C_{i+k}} \tag{16}$$

$$M_{C_{i,r}} = \sum_{k=1}^{n} W_{i+k}^2 \cdot D_{C_{i+k}} \tag{17}$$

$$D_{C_{i,r}} = S_{C_i} + M_{C_i} \tag{18}$$

By putting the values of $S_{C_i}$ and $M_{C_i}$ in eq. (18) from eq. (16) and eq. (17), respectively, and setting $W_{i+k}^1 + W_{i+k}^2 = 1$, we get the following equation.

$$D_{C_{i,r}} = \sum_{k=1}^{n} D_{C_{i+k}} \quad \forall 1 \le i \le C-2 \tag{19}$$

The total energy consumption of nodes in each corona is analyzed by calculating the energy consumption for receiving data by corona $i$ nodes. The energy consumed by each node during data reception from single hop and multihop neighbor nodes is given as:

$$e_{S_{C_i}} = Erx(r)\sum_{k=1}^{n}\left(D_{C_{i+k}} \cdot W_{i+k}^{1}\right) \tag{20}$$

$$e_{M_{C_i}} = Erx(2r)\sum_{k=1}^{n}\left(D_{C_{i+k}} \cdot W_{i+k}^{2}\right) \tag{21}$$

By adding eq. (20) and eq. (21), we get:

$$e_{i,r} = \left(Erx(r)\sum_{k=1}^{n} D_{C_{i+k}} \cdot W_{i+k}^{1}\right) + \left(Erx(2r)\sum_{k=1}^{n} D_{C_{i+k}} \cdot W_{i+k}^{2}\right) \tag{22}$$

$$e_{i,t} = \left(Etx(r)\sum_{k=1}^{n} D_{C_{i+k}} \cdot W_{i+k}^{1}\right) + \left(Etx(2r)\sum_{k=1}^{n} D_{C_{i+k}} \cdot W_{i+k}^{2}\right) + \left(Etx(dtx)\sum_{k=1}^{n} D_{C_{i+k}} \cdot W_{i+k}^{3}\right) \tag{23}$$

Thus, total energy consumption at corona $C_i$ is calculated as

$$e_i = e_{i,r} + e_{i,t} \tag{24}$$

The working of the BLOAD scheme is shown in Fig. 3. Working of the Hetero-BR scheme is the same as the Homo-BR scheme [5]. The only difference is that the energy levels are kept different in the Hetero-BR scheme on the basis of maximum and minimum energy consumption by nodes. The sum of the total energy of the network is the same of both schemes. We set different energy levels of nodes along with a dedicated deployment to achieve maximum stability and to avoid energy holes in the network.

It is worth mentioning here that our approach adjusts data distribution weights for energy balancing, i.e., balanced energy based transmissions. In other words, the transmit power levels are adjusted to indirectly cope with the dynamically changing underwater channel conditions.

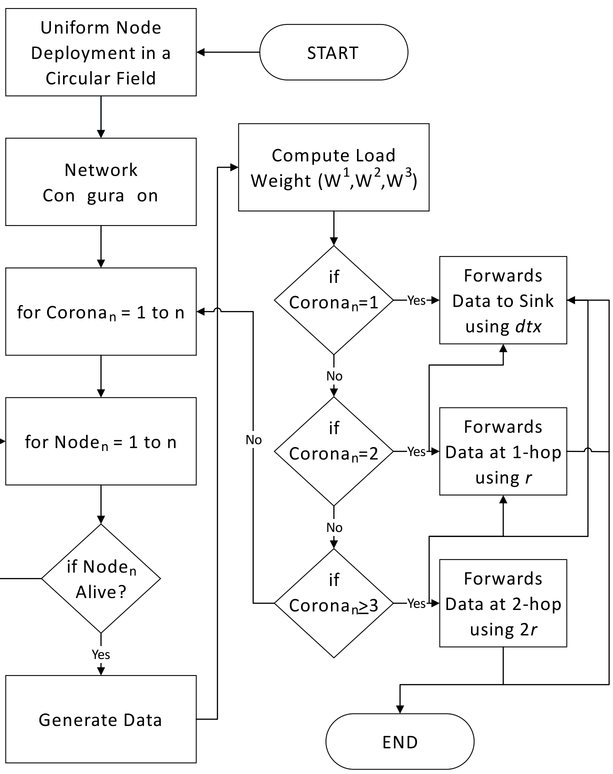



**FIGURE 3.** **Working flow of the BLOAD scheme.**

## IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the BLOAD scheme by comparing its simulation results with two selected existing schemes: NRF scheme [4] and BR scheme [5]. There are 50 sensor nodes deployed uniformly in a circular network field of radius $R = 1000m$. The width of each corona is $100m$. Each sensor node uses variable transmission ranges and generates data of 10 packet/s. Parameters of the Physical and MAC layers are kept the same as in [5].

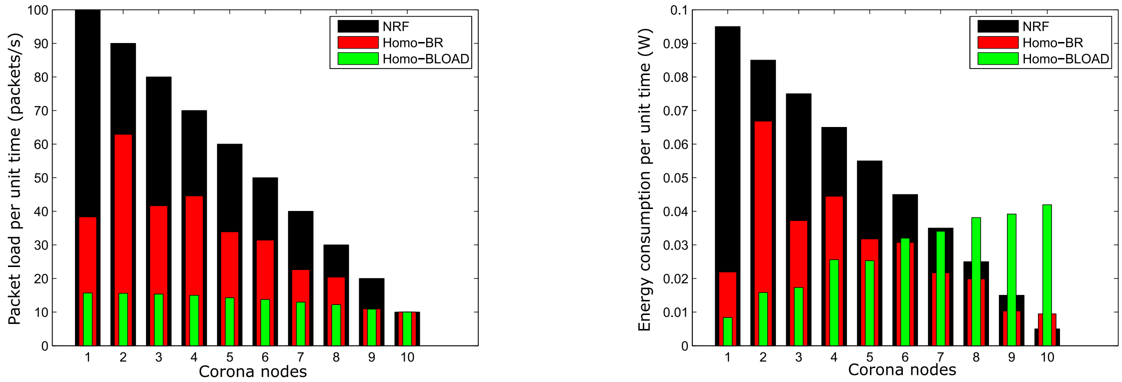
For performance evaluation we consider the following metrics.

1) **First Node Dead Time (FNDT):** The duration from establishment of the network to the time when the first node dies is called FNDT. FNDT also called stability period.
2) **All Node Dead Time (ANDT):** The period from FNDT to the time when all sensor nodes of the network are dead.
3) **Packet Load Distribution:** The distribution of the total data at each node for three transmissions, i.e., $r$, $2r$, $d_{tx}$.
4) **Residual Energy (RE):** The difference between the initial energy and the total energy consumed by each sensor nodes after transmitting and receiving data.
5) **Network Lifetime:** Duration from initialization of the network till ANDT or the network is totally disabled.

In the following subsections, we implement the BLOAD scheme in selected simulation environments.

### A. IMPLEMENTATION OF BLOAD IN HOMOGENEOUS ENVIRONMENT

We have implemented the BLOAD in homogeneous environment where all nodes in the network have the same energy level. Therefore, the initial energy of each node is set as $1J$. Fig. 4-9(a) shows load distribution per corona and Fig. 4-9(b) shows the energy consumption per unit time at each corona. In the NRF scheme, corona near the sink has a maximum load as compared to other coronas because the transmission range of each node in the network is $\{r\}$ and each corona except the outer most corona receives cumulative data of the previous corona. The nodes near the sink quickly deplete their energy due to maximum load and an energy hole is created near the sink.




(a) (b)

**FIGURE 4.** Comb:01: $\{W^1r, W^2 2r, W^3 dtx\}$. (a) Load distribution per corona. (b) Energy consumption of different coronas.

In the Homogeneous-Balanced Routing (Homo-BR) scheme, a packet load distribution matrix is derived for the transmission ranges $\{r, 2r\}$ to evenly distribute the energy consumption among all coronas. Data traffic load is minimized by less than 40 packet/s and the minimum energy consumption is achieved at one-hop neighbor corona of the sink in Homo-BR scheme using variable transmission ranges, i.e., $\{r, 2r\}$ but the energy consumption of two-hop neighbor corona of the sink is increased due to which all sensor nodes of corona 2 die within no time and an energy hole is created near the sink.

**TABLE 7.** Packet load distribution of BLOAD scheme.

| Corona | $W^1$ | $W^2$ | $W^3$ |
|---|---|---|---|
| Corona 1 | 1 | 0 | 0 |
| Corona 2 | 0.02 | 0.98 | 0 |
| Corona 3 | 0.23 | 0.35 | 0.42 |
| Corona 4 | 0.12 | 0.14 | 0.74 |
| Corona 5 | 0.19 | 0.25 | 0.56 |
| Corona 6 | 0.14 | 0.17 | 0.69 |
| Corona 7 | 0.15 | 0.18 | 0.67 |
| Corona 8 | 0.13 | 0.15 | 0.72 |
| Corona 9 | 0.11 | 0.13 | 0.76 |
| Corona 10 | 0.09 | 0.1 | 0.81 |

In the Homogeneous-BLOAD (Homo-BLOAD) scheme, we derive the packet load distribution matrix as shown in table 7 for the mixed routing, i.e., $\{r, 2r, dtx\}$ to balance the energy consumption of all coronas for maximum network lifetime. In the Homo-BLOAD scheme, the total traffic load at each corona is balanced because some fraction of the data is directly sent to the sink and the energy consumption among all coronas is balanced using hop-by-hop and direct transmissions. It is found from the simulation results that the energy consumption of corona 10 nodes in the Homo-BLOAD scheme is greater than that of the Homo-BR scheme because data packets are sent directly as well as hop-by-hop to the sink using the transmission ranges $\{r, 2r, dtx\}$ while, the total data in Homo-BR scheme is sent using the transmission ranges $\{r, 2r\}$.

The overall packet load distribution of all coronas is balanced in the Homo-BLOAD scheme because all coronas send a fraction of data of the total data traffic direct to the sink using the transmission range $\{dtx\}$ and the remaining fraction of data of the total data traffic is sent to next 1-hop and 2-hop coronas using the transmission ranges $\{r\}$ and $\{2r\}$. The minimum data traffic load at 1-hop and 2-hop away neighbors of the sink leads to a minimum energy consumption of corona 1 nodes and corona 2 nodes in the Homo-BLOAD scheme as discussed in Section III and it is shown in Fig. 8a and Fig. 8b.

In the Homo-BLOAD scheme, the total data traffic is forwarded with three data load weights to the sink using three transmission ranges. We get six different scenarios from eq. (14) which has the combination of data load weights and transmission ranges. We have discussed the simulation results of all the scenarios in the upcoming subsections.

### 1) COMBINATION:01 (COMB:01)

In this scenario, the small fraction of data of the total data traffic is sent to the adjacent 1-hop neighbor of each node with data load weight $W^1$ using the transmission range $\{r\}$. The medium data fraction of the total data is sent to next 2-hop neighbors of a node with data load weight $W^2$ using the transmission range $\{2r\}$ and the large portion of the total data traffic is directly sent to the sink with load weight $W^3$ using the transmission range $\{dtx\}$. The results of the packet load distribution and energy consumption of scenario Comb:01 are shown in Fig. 4a and Fig. 4b. The overall packet load distribution is balanced in this scenario because of the direct transmission of the large data portion to the sink. The energy consumption of the last corona is higher than all coronas

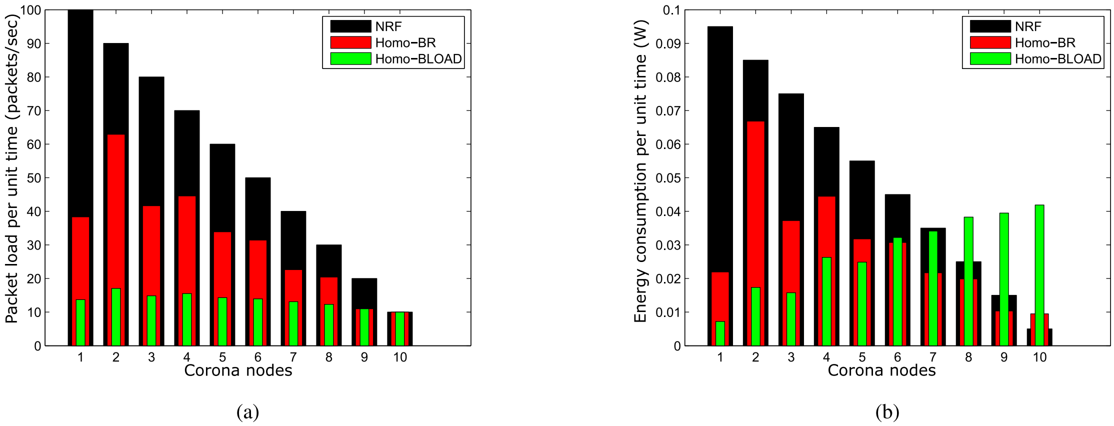



**FIGURE 5.** Comb:02: $\{W^1 2r, W^2 r, W^3 dtx\}$. (a) Load distribution per corona. (b) Energy consumption of different coronas.

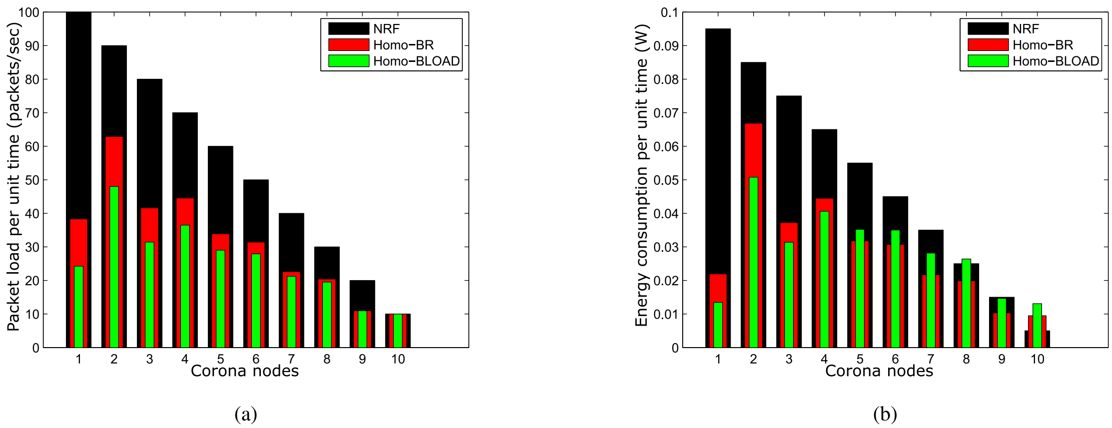



**FIGURE 6.** Comb:03: $\{W^1 dtx, W^2 r, W^3 2r\}$. (a) Load distribution per corona. (b) Energy consumption of different coronas.

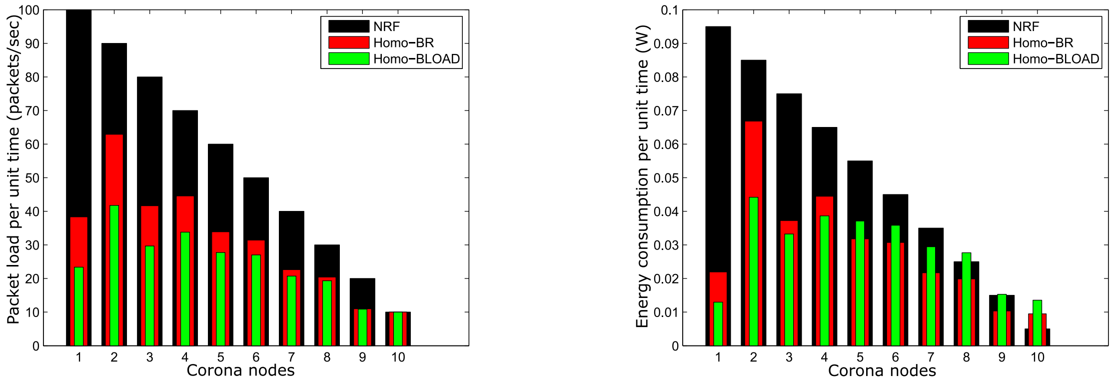
because distance of the last corona is greater than the rest of the coronas. The energy consumption of a corona is decreased as much as its distance from the sink because the high energy is required to send large data portions of the total data traffic directly to the sink using the transmission range $\{dtx\}$. In Comb:01, the energy consumption of the neighbors near the sink is decreased but the overall energy consumption of the network is not balanced.

### 2) COMBINATION:02 (COMB:02)

The medium data fraction of the total traffic is sent with data load $W^2$ to the next 1-hop neighbor using the transmission range $\{r\}$ and the small data fraction is forwarded to 2-hop neighbor of a node with a data load weight $W^3$ using the transmission range $\{2r\}$ in Comb:02. The third transmission remains the same as Comb:01. Fig. 5a and Fig. 5b show almost the same behaviour as Comb:01 because we observe that the transmission of a large data fraction mainly affects the packet load distribution and the total energy consumption of the network as well. We found that the traffic load and the energy consumption at corona 2 is relatively high because of sending the medium data fraction with $W^2$ using the transmission range $\{r\}$. We consider the sensor nodes which adjust their transmission power according to the transmission distance. The total energy consumption of the network is not balanced in Comb:02 because the energy is consumed in data transmission at long distance by the coronas which are far from the sink.

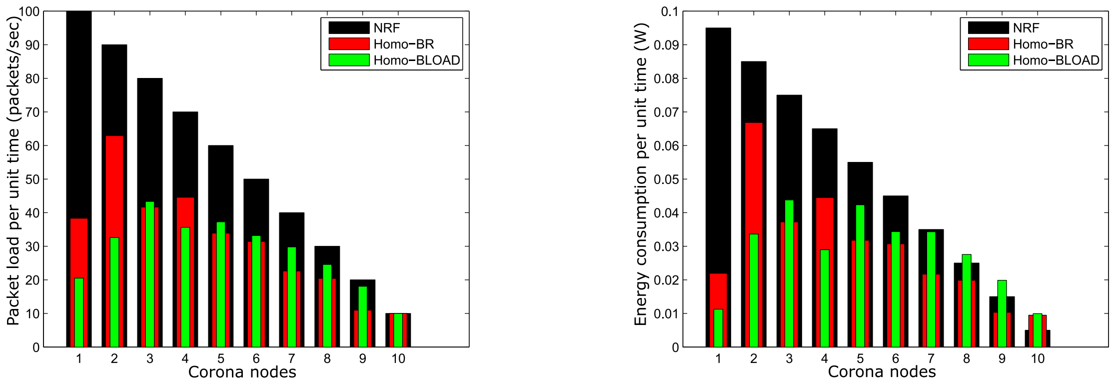
### 3) COMBINATION:03 (COMB:03) AND COMBINATION:04 (COMB:04)

In Comb:03, a small fraction of data is sent directly to the sink with the data load weight $W^1$ using the transmission range $dtx$ and the medium fraction of data is sent with the data load weight $W^2$ using the transmission range $\{r\}$. In Comb:04, the only difference from Comb:03 is that the medium fraction of data is directly sent to the sink with the load weight $W^2$ using the transmission range $dtx$ and a small fraction of data is forwarded with a data load weight $W^1$ using the transmission range $\{r\}$. The large fraction of data is forwarded to the adjacent 2-hop neighbor of a node with the data load weight $W^3$ using the transmission range $\{2r\}$ in both Comb:03 and Comb:04. The discussed scenario of three different transmissions of Comb:03 and Comb:04 shows the same behaviour as the Homo-BR scheme because a large fraction of data is sent using the transmission range $\{2r\}$ as in Homo-BR scheme. Fig. 6a and Fig. 7a show the packet load distribution of Comb:03 and Comb:04, respectively. We




(a) (b)

**FIGURE 7.** **Comb:04: {$W^1r$, $W^2dtx$, $W^3 2r$}. (a) Load distribution per corona. (b) Energy consumption of different coronas.**




(a) (b)

**FIGURE 8.** **Comb:05: {$W^1 2r$, $W^2dtx$, $W^3r$}. (a) Load distribution per corona. (b) Energy consumption of different coronas.**

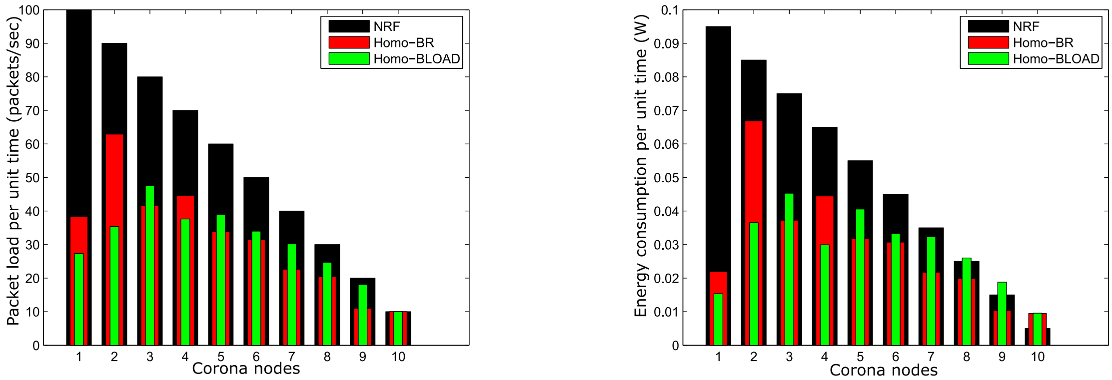
observe that the fraction of data sent using the two transmission ranges $\{r\}$ and $\{2r\}$ affect the packet load distribution while the rest of the data is sent directly to the sink in the third transmission $\{dtx\}$. The energy consumption of Comb:03 and Comb:04 is greater than the Homo-BR scheme as shown in Fig. 6b and Fig. 7b because in the Homo-BLOAD scheme the total data traffic is forwarded using three transmission ranges $\{r, 2r, dtx\}$. Corona 2 nodes which are 2-hop neighbors of the sink consume more energy than other corona nodes of the network. Thus, sensor nodes in corona 2 die within no time. The overall packet load distribution and the energy consumption of the network is not balanced as shown in Fig. 6a, Fig. 6b, Fig. 7a and Fig. 7b.

#### 4) COMBINATION:05 (COMB:05) AND COMBINATION:06 (COMB:06)

We observe that in Comb:05 and Comb:06, the packet load distribution is balanced as shown in Fig. 8a and Fig. 9a. It is notable that the energy consumption of 1-hop and 2-hop neighbors of the sink is minimized as discussed in section III. The overall energy consumption in both Comb:05 and Comb:06 is balanced as shown in Fig. 8b and Fig. 9b because the small and medium fractions of data of the total data traffic are forwarded to the 2-hop neighbor of a node and directly to the sink using the transmission ranges $\{2r\}$ and $\{dtx\}$. The remaining large fraction of data is forwarded to the adjacent neighbor node of each node with data load weight $W^3$ using the transmission range $r$, due to which the packet load distribution of the network is balanced which leads to a balanced energy consumption of the network. Our goal is to minimize the packet load distribution and the energy consumption of 1-hop and 2-hop neighbor nodes of the sink to avoid the energy sink hole problem. It is noticeable that the packet load on corona 1 and corona 2 nodes in Comb:05 (Fig. 8a) is about 5% less than Comb:06 (Fig. 9a). The energy consumption of corona 1 and 2 nodes in Comb:05 (Fig. 8b) is also less than Comb:06 (Fig. 9b) because in Comb:05 the medium fraction of the data is sent directly to the sink with a load weight $W^2$ using the transmission range $\{dtx\}$ which minimizes the data load traffic on corona nodes which are near the sink. Thus, we find an optimal solution to avoid the energy sink hole problem in Comb:05.

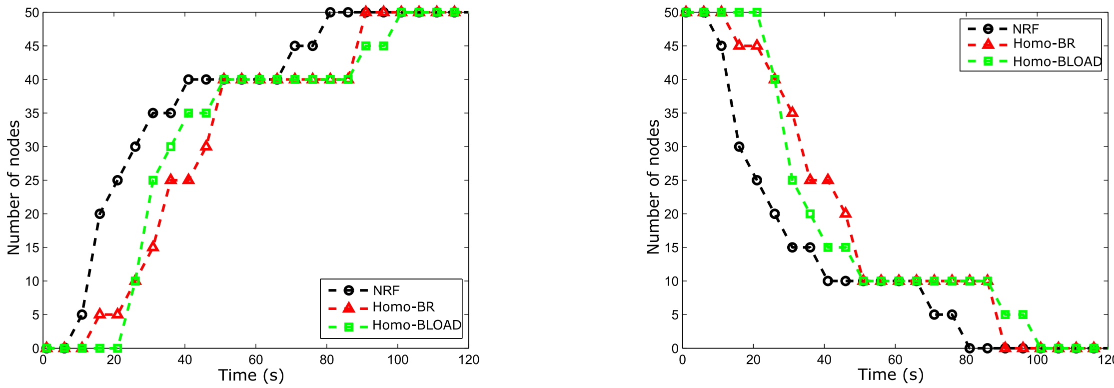
#### 5) FNDT AND ANDT OF HOMO-BLOAD

In Fig. 10a, it is shown that FNDT of Homo-BLOAD scheme is 20 s, which shows stability of the network.




(a) (b)

**FIGURE 9.** **Comb:06: $\{W^1 dtx, W^2 2r, W^3 r\}$. (a) Load distribution per corona. (b) Energy consumption of different coronas.**




(a) (b)

**FIGURE 10.** **FNDT and ANDT of the Homo-BLOAD scheme. (a) No of dead nodes. (b) No of alive nodes.**

From Fig. 8a and Fig. 8b, we can easily observe that the load distribution is in direct relation with the energy consumption of sensor nodes. The stability period of the Homo-BLOAD scheme is longer than the other two schemes because the total data load is evenly distributed among all nodes in all coronas which results in balanced energy consumptions. In the Homo-BR scheme, the data load is minimized at 1-hop neighbor nodes of the sink because its 2-hop neighbor nodes send the maximum data load directly to the sink using the transmission range $\{2r\}$. We can also say that corona 2 pays the cost of maximum energy consumption by minimizing the data load at corona 1 because sensor nodes of corona 2 are 1-hop neighbors of the sink using the transmission range $\{2r\}$. Due to the maximum energy consumption of sensor nodes in corona 2, they die earlier than the other sensor nodes. Thus, the stability of Homo-BR scheme is 10 s which is 10 s less than the Homo-BLOAD scheme. The stability period of the NRF scheme is shorter than the Homo-BLOAD scheme because in the NRF scheme, the energy consumption of sensor nodes in corona 1 is maximum due to the non-uniform data load which causes premature death of sensor nodes in corona 1. The FNDT of the NRF scheme is 5 s, which is 15 s less than the Homo-BLOAD scheme because the sensor nodes in corona 1 in the NRF scheme die within no time due to the unbalanced data load. FNDT of the Homo-BR scheme starts 10 s before than the Homo-BLOAD scheme and ANDT ends at 90 s. While the ANDT of the Homo-BLOAD scheme ends at 100 s. Thus, the ANDT of the Homo-BR and the Homo-BLOAD scheme is the same because both schemes use variable transmission ranges $\{r, 2r\}$. The ANDT shows the instability period and the NRF scheme has less instability period than the other two schemes as shown in Fig. 10b. The lifetime of the Homo-BLOAD scheme is better than the selected schemes because the balanced load distribution leads to a balanced energy consumption of the network. We can observe that the network lifetime of the Homo-BLOAD scheme is 100 s while, the network lifetime of the two selected schemes, NRF and Homo-BR is almost 80 s and 90 s respectively. We can observe that 80% sensor nodes of the network die after 40 s in the NRF scheme. While, in the Homo-BR scheme, 50% nodes are still alive at 40 s. When sensor nodes near the sink die, the previous coronas sensor nodes cannot report their data to the sink because both NRF and Homo-BR schemes use the transmission ranges $\{r\}$ and $\{r, 2r\}$ respectively.

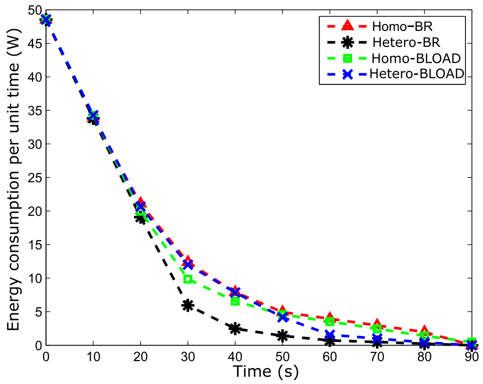



**FIGURE 11.** Energy consumption of the proposed schemes.

The Homo-BLOAD scheme tackles this problem using adjustable transmission power sensor nodes which can report directly to the sink using transmission ranges $\{r, 2r, dtx\}$ as well as hop-by-hop transmission i.e., $\{r, 2r\}$ and all sensor nodes start direct transmission if no sensor nodes are available in the next hop corona. Therefore, the network lifetime of the Homo-BLOAD scheme is longer than the other two existing schemes.

### B. IMPLEMENTATION OF BR AND BLOAD SCHEMES IN HETEROGENEOUS ENVIRONMENTS

The energy consumption of the Hetero-BR scheme which is implemented in heterogeneous environments where all nodes have different energy levels, is shown in Fig. 11, is more than the Homo-BR and Homo-BLOAD schemes because all nodes are continuously forwarding and receiving data while in Homo-BR and Homo-BLOAD schemes, the nodes near the sink die earlier due to which the nodes of the previous coronas do not forward data to the sink. Thus, the energy consumption of the Homo-BR and Homo-BLOAD schemes is less than that of the Hetero-BR scheme. In Fig. 11 the total energy consumption of the proposed techniques looks almost same at the start of the network initialization because all the nodes of the techniques are alive at the start and their accumulative energy consumption is same. The FNDT and ANDT of the Hetero-BR and Hetero-BLOAD schemes are shown in Fig. 12a and Fig. 12b. The stability period of the Hetero-BR scheme is 15% better than that of the Homo-BR scheme and it is 5% better than that of the Homo-BLOAD scheme. Therefore, the network is stable upto 25 s as shown in Fig. 12b. The problem discussed above is solved by setting heterogeneous energy levels of each corona node. Therefore, we can observe a notable difference in stability of the network, which is high as compared to the homogeneous schemes. The implementation of the BLOAD scheme in heterogeneous and homogeneous environments is performed and residual energy of both schemes is shown in Fig. 13a and Fig. 13b. It is observed that the energy consumption of the Homo-BLOAD scheme is higher than that of the Hetero-BLOAD scheme. Therefore, the sensor nodes with the high energy consumption are assigned maximum energy level in the Hetero-BLOAD scheme. The residual energy of the Hetero-BLOAD scheme is maximum than that of the Homo-BLOAD scheme because of the different energy levels assigned to high energy consumption corona nodes. Hence, the scheme having dedicated deployment along with the heterogeneous energy is suitable for continuous monitoring applications in UWSNs.

## V. PERFORMANCE TRADEOFFS

The BLOAD scheme shows a tradeoff between data load balancing and energy consumption of the network. We achieve load balancing by adjusting the transmission power level of the sensor nodes. Nodes forward data to the sink directly as well as hop-by-hop in the BLOAD scheme. In order to avoid energy holes, we minimize the data load on 1-hop and 2-hop neighbors of the sink. The load is distributed among all nodes to minimize the energy consumption at nodes near the sink. For load balancing, the sensor nodes at long distance directly forward data to the sink using a direct transmission range and deplete relatively high energy. Thus, the Homo-BLOAD routing protocol achieves balanced load distribution

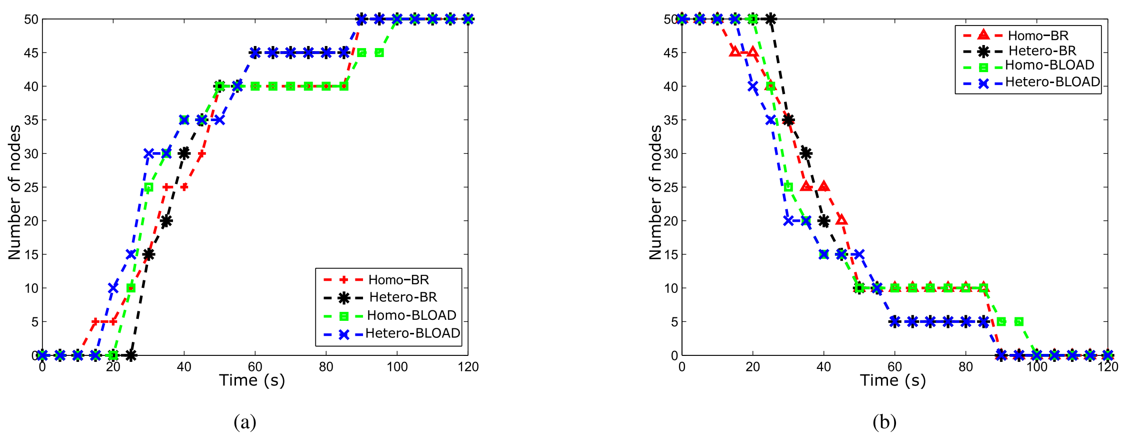
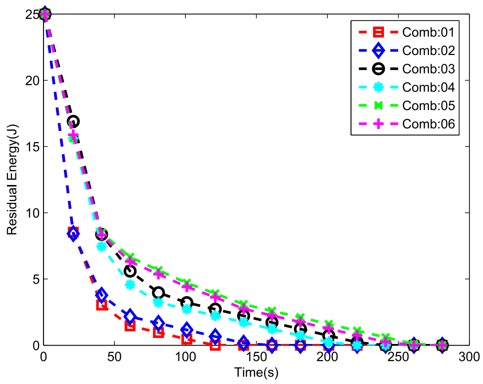
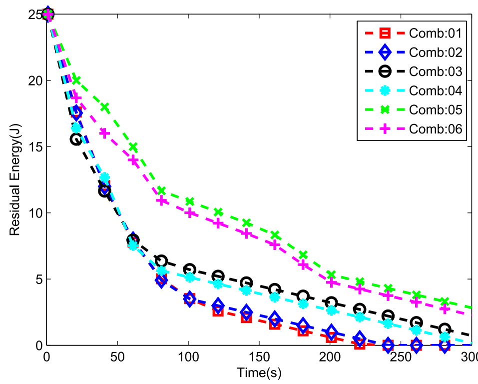



**FIGURE 12.** FNDT and ANDT of the proposed schemes. (a) No of dead nodes. (b) No of alive nodes.




(a)




(b)

**FIGURE 13.** **Residual energy for all possible combinations of the transmission ranges and the load weights. (a) Residual energy of the Homo-BLOAD scheme. (b) Residual energy of the Hetero-BLOAD scheme.**

**TABLE 8.** **Performance trade-offs by proposed and existing schemes.**

| Protocols | Techniques | Parameters achieved | Cost to pay |
|---|---|---|---|
| **NRF** | Nominal Communication Range Forwarding $\{r\}$ | Minimum Energy Consumption | Unbalanced Data Load and Unbalanced Energy Consumption |
| **Homo-BR** | Variable Transmission Range Forwarding $\{r, 2r\}$ | Data Load Balancing and Minimum Energy Consumption | Stability Period and Unbalanced Energy Consumption |
| **Hetero-BR** | Variable Transmission Range Forwarding $\{r, 2r\}$ | Stability Period | Maximum Energy Consumption |
| **Homo-BLOAD** | Mixed Transmissions Range Forwarding $\{r, 2r, dtx\}$ | Balanced Energy Consumption and Balanced Load Distribution | Energy Consumption Instability Period |
| **Hetero-BLOAD** | Mixed Transmissions Range Forwarding $\{r, 2r, dtx\}$ | Stability Period | Energy Consumption |

at the cost of high energy consumption as shown in table 8. Each sensor node in the BLOAD scheme transmits data using variable transmission ranges. Therefore, the energy consumption of the network is maximum in the BLOAD scheme as compared to the existing schemes. Sensor nodes in the Homo-BR scheme are out of energy in high energy consumption corona due to unbalanced load. In the proposed schemes, sensor nodes forward data using variable transmission ranges $\{r, 2r, dtx\}$ for load balancing. Therefore, energy consumption is high. Also, we have improved the overall lifetime of the network in the proposed schemes in terms of data packets received by the sink after the death of one-hop and two-hop neighbors of the sink because in the previous schemes the network became disable after the death of nodes near the sink. In the Hetero-BR scheme, the nodes with high energy consumption are assigned high energy level and the nodes with low energy consumption are assigned low energy levels. Therefore, the stability of the network is achieved by using the Hetero-BR scheme at the cost of high energy consumptions.

## VI. CONCLUSION AND FUTURE WORK

Energy balancing in UWSNs is one of the key requirements because of limited energy resources. In UWSNs, the sensor nodes consume high energy when there is an unbalanced load. We proposed a BLOAD scheme to balance the load and to avoid energy holes in the network. The BLOAD scheme is specifically designed to solve the energy hole problem when a node does not find a forwarder node in the next corona to reach the sink. Previously, in NRF and BR schemes, nodes near the sink in corona 1 and corona 2 were out of energy because of unbalanced load and energy hole was formed near the sink and the network was totally disabled. At the end, most of the sensor nodes of the network which were far from the sink were alive and had maximum residual energy. In the BLOAD scheme the discussed problem is solved and sensor nodes continuously report data to the sink, even nodes are out of energy in the next corona. The stability in the network is achieved by implementing sensor nodes in a heterogeneous simulation environment. The results showed that BLOAD outperforms existing schemes in terms of stability period and lifetime.

In the future, we will work on detecting the energy holes in UWSNs using analytical modelling. The energy hole repair technique is also interesting in proactive and reactive modes of a network. More importantly, changes in node locations due to drift or mobility will give rise to additional challenges in the proposed scheme. We have plans to address these challenges in the future.

## ACKNOWLEDGEMENT

This project was full financially supported by the King Saud University, through Vice Deanship of Research Chairs.

## REFERENCES

[1] I. F. Akyildiz, P. Wang, and S.-C. Lina, "SoftWater: Software-defined networking for next-generation underwater communication systems," *Ad Hoc Netw.*, vol. 46, pp. 1–11, Aug. 2016.

[2] H. Yu, N. Yao, T. Wang, G. Li, Z. Gao, and G. Tan, "WDFAD-DBR: Weighting depth and forwarding area division DBR routing protocol for UASNs," *Ad Hoc Netw.*, vol. 37, pp. 256–282, Feb. 2016.

[3] M. Ayaz and A. Abdullah, "Underwater wireless sensor networks: Routing issues and future challenges," in *Proc. 7th Int. Conf. Adv. Mobile Comput. Multimedia*, Dec. 2009, pp. 370–375.

[4] H. M. Ammari and S. K. Das, "Promoting heterogeneity, mobility, and energy-aware voronoi diagram in wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 19, no. 7, pp. 995–1008, Jul. 2008.

[5] C. Zidi, F. Bouabdallah, and R. Boutaba, "Routing design avoiding energy holes in underwater acoustic sensor networks," *Wireless Commun. Mobile Comput.*, vol. 16, no. 14, pp. 2035–2051, Oct. 2016.

[6] I. Azam *et al.*, "Avoiding energy holes in underwater wireless sensor networks with balanced load distribution," in *Proc. 10th IEEE Int. Conf. Complex, Intell., Softw. Intensive Syst. (CISIS)*, Fukuoka, Japan, Jul. 2016, pp. 341–350.

[7] W. Guo, Z. Liu, and G. Wu, "An energy-balanced transmission scheme for sensor networks," in *Proc. 1st Int. Conf. Embedded Netw. Sensor Syst.*, Nov. 2003, pp. 300–301.

[8] C. Efthymiou, S. Nikoletseas, and J. Rolim, "Energy balanced data propagation in wireless sensor networks," in *Proc. 18th Int. Parallel Distrib. Process. Symp. (IPDPS)*, Apr. 2004, p. 225

[9] O. Powell, P. Leone, and J. Rolim, "Energy optimal data propagation in wireless sensor networks," *J. Parallel Distrib. Comput.*, vol. 67, no. 3, pp. 302–317, Mar. 2007.

[10] H. Zhang and H. Shen, "Balancing energy consumption to maximize network lifetime in data-gathering sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 20, no. 10, pp. 1526–1539, Oct. 2009.

[11] J. Cao, J. Dou, and S. Dong, "Balance transmission mechanism in underwater acoustic sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 3, p. 429340, 2015.

[12] N. Javaid, M. Shah, A. Ahmad, M. Imran, M. I. Khan, and A. V. Vasilakos, "An enhanced energy balanced data transmission protocol for underwater acoustic sensor networks," *Sensor*, vol. 16, no. 4, p. 487, 2016.

[13] K. Latif, N. Javaid, A. Ahmad, Z. A. Khan, N. Alrajeh, and M. I. Khan, "On energy hole and coverage hole avoidance in underwater wireless sensor networks," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4431–4442, Jun. 2016.

[14] P. Jiang, J. Liu, B. Ruan, L. Jiang, and F. Wu, "A new node deployment and location dispatch algorithm for underwater sensor networks," *Sensors*, vol. 16, no. 1, p. 82, 2016.

[15] H. Luo, Z. Guo, K. Wu, F. Hong, and Y. Feng, "Energy balanced strategies for maximizing the lifetime of sparsely deployed underwater acoustic sensor networks," *Sensors*, vol. 9, no. 9, pp. 6626–6651, 2009.

[16] Z. Li, N. Yao, and Q. Gao, "Relative distance based forwarding protocol for underwater wireless networks," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 2, Feb. 2014.

[17] T. Ali, L. T. Jung, and I. Faye, "End-to-end delay and energy efficient routing protocol for underwater wireless sensor networks," *Wireless Pers. Commun.*, vol. 79, no. 1, pp. 339–361, Nov. 2014.

[18] Y. Zhang, J. Liang, S. Jiang, and W. Chen, "A localization method for underwater wireless sensor networks based on mobility prediction and particle swarm optimization algorithms," *Sensors*, vol. 16, no. 2, p. 212, 2016.

[19] G. Liu and C. Wei, "A new multi-path routing protocol based on cluster for underwater acoustic sensor networks," in *Proc. Int. Conf. Multimedia Technol. (ICMT)*, Jul. 2011, pp. 91–94.

[20] A. Sanchez, S. Blanc, P. Yuste, and J. Serrano, "A low cost and high efficient acoustic modem for underwater sensor networks," in *Proc. IEEE-Spain OCEANS*, Jun. 2011, pp. 1–10.

[21] M. C. Domingo, "Overview of channel models for underwater wireless communication networks," *Phys. Commun.*, vol. 1, no. 3, pp. 163–182, 2008.

[22] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, Los Angeles, CA, USA, Sep. 2006, pp. 41–47.

[23] L. Berkhovskikh and Y. Lysanov, *Fundamentals of Ocean Acoustics*. New York, NY, USA: Springer, 1982.

**IRFAN AZAM** received the master's degree from the Department of Computer Science, COMSATS Institute of Information Technology, Islamabad, Pakistan, under the supervision of Dr. N. Javaid. He is currently a Lecturer with the Shaheed Zulfikar Ali Bhutto Institute of Science and Technology, Islamabad.

**NADEEM JAVAID** (S'08–M'11–SM'16) received the bachelor's degree in computer science and physics from Gomal University, Dera Ismail Khan, KPK, Pakistan, in 1995, the master's degree in electronics from Quid-I-Azam University, Islamabad, Pakistan, in 1999, and the Ph.D. degree from the University of Paris-Est, France, in 2010. He is currently an Associate Professor and the Founding Head of the ComSens (Communications over Sensors) Research Group, Department of Computer Science, COMSATS Institute of Information Technology, Islamabad. He has supervised 60 M.S. and six Ph.D. theses. He has published over 350 articles in peer-reviewed technical journals and international conferences. His research interests include wireless ad hoc networks, wireless sensor networks, and energy optimization in smart grids. He has been an Organizer and a TPC Member of several international conferences, like, BWCCA, AINA, ANT, SEIT, Globecom, ICC, and IWCMC. He is an Editor and a Reviewer of many journals.

**ASHFAQ AHMAD** (S'13) received the B.S. and M.S. degrees in electrical engineering with specialization in wireless sensor networks and energy optimization in smart grids from the COMSATS Institute of Information Technology, Islamabad, Pakistan, in 2013 and 2015, respectively, under the supervision of Dr. N. Javaid. He is currently pursuing the Ph.D. degree with The University of Newcastle, Australia. He has published 24 research publications in ISI-indexed international journals and conferences. His research interests include addressing fundamental flaws in routing and MAC protocols for WSNs/UWSNs/WBANs, and load forecasting and demand response in smart grid. He served as a Reviewer and a TPC Member of prestigious international journals and conferences/workshops; the IEEE Transactions on Industrial Informatics, *Ad hoc Networks*, the 13th International Conference on Frontiers of Information Technology, the International Workshop on Body Area Sensor Networks, and *Evidence-Based Complementary and Alternative Medicine*.

**WADOOD ABDUL** (M'12) received the Ph.D. degree in signal and image processing from the University of Poitiers, France, in 2011. He is currently an Assistant Professor with the Department of Computer Engineering, CCIS, King Saud University. His research interests are focused on color image watermarking, multimedia security, steganography, fingerprinting, and biometric template protection.

**AHMAD AL-MOGREN** received the Ph.D. degree in computer sciences from Southern Methodist University, Dallas, TX, USA, in 2002. He was an Assistant Professor of Computer Science and a member of the Scientific Council, Riyadh College of Technology. He also served as the Dean of the College of Computer and Information Sciences and the Head of the Council of Academic Accreditation, Al Yamamah University. He is currently an Associate Professor and the Vice Dean for the development and quality with the College of Computer and Information Sciences, King Saud University, Saudi Arabia. His research areas of interest include mobile and pervasive computing, computer security, sensor and cognitive network, and data consistency. He has served as a Guest Editor for several computer journals.

**ATIF ALAMRI** (M'12) received the B.Sc. and M.Sc. degrees in information systems from the College of Computer and Information Sciences (CCIS), King Saud University (KSU), Riyadh, Saudi Arabia, in 2000 and 2004, respectively, and the Ph.D. degree in computer science from the School of Information Technology and Engineering, University of Ottawa, Canada, in 2010. He is currently an Associate Professor with the Information Systems Department, CCIS, KSU. He is one of the founding members of the Chair of Pervasive and Mobile Computing, CCIS, KSU, and successfully managing its research program, which transformed the chair as one of the best chairs of research excellence in the college. He is also acting as an Assistant Vice-Rector of Technical, Vice President's Office for Quality and Development, KSU. His research areas of interest are multimedia assisted health systems, ambient intelligence, service-oriented architecture, multimedia cloud, sensor-cloud, Internet of Things, big data, mobile cloud, social network, and recommender system.