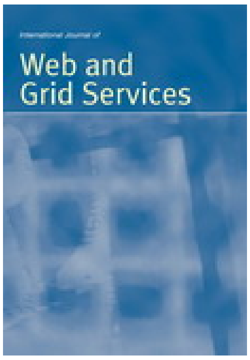

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A new joint geo-opportunistic routing scheme in duty cycled internet of underwater things

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Abstract: The inefficient consumption of energy is a critical challenge in internet of underwater things (IoUTs) because of difficult replenishment of energy. It is possible to overcome this difficulty by introducing sleep-awake scheduling for energy conservation. In this paper, two schemes have been proposed focusing on energy efficiency: geo-opportunistic asynchronous sleep-awake scheduling routing technique (GOASST) and coordinated sink mobility-based GOASST (CSM-GOASST). By exploiting geographic and opportunistic routing paradigms, the advantages like path diversity and improved reliable communication have been achieved. Moreover, the coordinated sink mobility in multi-sink architecture introduced in CSM-GOASST exhibits potential in reducing end-to-end network delay. In CSM-GOASST, an optimal sink position helps to find the shortest path to deliver data to the destination. In addition, linear programming-based mathematical modelling is carried out for performance parameters to find feasible solutions. The performance of the proposed schemes is evaluated by performing extensive simulations.

Keywords: connectivity holes; coordinated mobility; fraction of void nodes; internet of underwater things; IoUTs; opportunistic routing; packet delivery; potential neighbour; sleep-awake scheduling.

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1 Introduction

Internet of underwater things (IoUTs) has emerged as an establishing technology for a wide range of applications, including monitoring, event detection, target tracking, etc. These applications require long-term deployment; therefore, an energy efficient mechanism is needed. Since it is infeasible to recharge batteries in a harsh underwater environment, therefore, there is a need to imply routing strategies focusing on energy conservation (Zia et al., 2021; Sakamoto et al., 2019).

In addition, the data transmission in IoUTs is prone to failure due to channel fading and attenuation. In order to achieve reliable data delivery, retransmission mechanisms are commonly used in multi-hop routing schemes (Du et al., 2021). However, they consume a lot of energy. It is proposed that opportunistic routing is used to cater this problem by spatial diversity (Latif et al., 2020). A node broadcasts the data packet to a forwarding set of nodes. Moreover, hidden terminal problem is solved by the involvement of multiple nodes that can overhear each other's transmissions in opportunistic routing (Khan et al., 2019). Furthermore, in the case of bad link quality, the availability of multiple nodes in the forwarding set ensures successful data delivery and reduces energy consumption caused by retransmissions (Karim et al., 2021a; Khan et al., 2022). Region-based routing is another supportive paradigm for reliable data delivery, which relies on position information to transmit data towards the ultimate destination. Thus, region-based routing can help in achieving reliable packet delivery with low energy cost (Menaga et al., 2021; Javaid et al., 2019a).

Usually, sensor nodes perform sensing and processing much often as compared to communication tasks, which means that most of the time transceiver of sensor nodes stays in an idle listening mode (Sher et al., 2018; Alharbi et al., 2022). When, there is no data communication, the sensor node goes to inactive state and its communication module is turned off. For example, energy consumption of a MICAz node is 3 μW and 60 μW in sleep mode and idle mode, respectively (Su et al., 2021a). It depicts the difference of energy consumption between sleep mode and idle mode. Duty cycle-based schemes are energy-efficient. However, these schemes face some challenges, e.g., sleep latency because the sender node has to wait for receiver node to be awake. Moreover, in certain cases, the broadcast data does not reach to every neighbour node because of inactive state of some nodes (Coutinho and Boukerche, 2021). Thus, saving energy cost increases communication delays.

In general, synchronous schemes involve high maintenance cost in IoUTs (Bhushan et al., 2021). In the asynchronous duty cycled schemes, sensor nodes wake-up independently. Therefore, they can be implemented locally without additional overhead cost. However, in dynamic topology, frequent control packet exchange is performed to extract information of sensor nodes and keep the connectivity intact (Su et al., 2021b). Moreover, duty cycling along with geo-opportunistic routing benefits in achieving high throughput with reduced energy cost (Ahmed et al., 2018).

In this paper, geo-opportunistic asynchronous sleep-awake scheduling routing technique geo-opportunistic asynchronous sleep-awake scheduling routing technique (GOASST) and coordinated sink mobility-based GOASST (CSM-GOASST) are proposed. The following key points are considered to specify the features and the novelty of the proposed work.

- In GOASST (presented in Section 3), the effect of wake-up duration and wake-up rate of a node on its energy consumption is discussed. The proposed scheme improves the data delivery with reduced energy cost by jointly considering opportunistic routing and asynchronous sleep-awake scheduling.
- In CMS-GOASST, sink mobility is introduced in GOASST to provide maximum coverage in the network for maximising data delivery with reduced end-to-end delay. Furthermore, sink utilisation ratio in GOASST is considered by deploying multiple sinks in the three dimensional field.
- Linear programming-based mathematical modelling is performed for performance parameters in order to find feasible solutions (presented in Section 5). As final step, extensive simulations are conducted for performance evaluation.

Section 2 presents the related work. Sections 3 and 4 provide details about GOASST and CSM-GOASST followed by mathematical modelling in Section 5. Simulations results are presented in Section 6. Finally, the paper is concluded in Section 7 along with future directions.

2 Related work

In traditional deterministic routing schemes, the purpose of forwarder selection is to relay data towards the destination with minimum energy cost and average delay (Raza et al., 2017). On the other hand, opportunistic routing is a promising paradigm to deal with the unreliable links in wireless medium because of the selection of forwarder set to avoid void regions. Existing works have exploited opportunistic routing for energy efficiency in sensor-based networks (Khan et al., 2017; Javaid et al., 2017; Hung et al., 2013).

Geographic and opportunistic routing with depth adjustment-based topology control for communication recovery (GEDAR) is utilised in Coutinho et al. (2014) and Kheirabadi and Mohamad (2013), while selecting a potential forwarder based on the advancement towards the destination. In Coutinho et al. (2014), a geo-opportunistic routing scheme is proposed coping with the communication voids by its depth adjustment recovery mode. A forwarder set is selected in which each node is prioritised according to its advancement towards destination. The node that secures the highest normalised advancement towards the destination is chosen as a potential forwarder. To deal with the communication voids, depth-based recovery mechanism provides better data delivery at the cost of high energy consumption. In Adhinugraha et al. (2020), multi-gateways are considered to reduce the network latency and failure issue. In Adhinugraha et al. (2021a), order k-hop is utilised to identify the coverage of routers as the backup gateway. It provides the facility with minimum hop distance that enhances the capability of the network. In Adhinugraha et al. (2021b), a better gateway diversion strategy is introduced that measures the fault tolerance and provides an optimal path to maintain the network connectivity. In Noh et al. (2013), two hop depth information and depth counts are considered for the selection of forwarder nodes. Firstly, a beacon message is initiated by a node that contains coordinates of node, hop count and data forwarding direction. Secondly, the opportunistic directional forwarding is performed to send the data packet upward towards the water surface. However, the energy consumption at idle listening is not addressed in the aforementioned studies. It is worth noticing that this work presents a combined geo-opportunistic paradigm with the idea of sleep-awake scheduling. The primary objectives of duty cycling include minimisation of energy consumption and prolongation of network lifetime. Energy efficient duty cycling schemes reported in literature are categorised into synchronous and asynchronous scheduling schemes. Some of them, which are close to proposed work, are highlighted in the following sections.

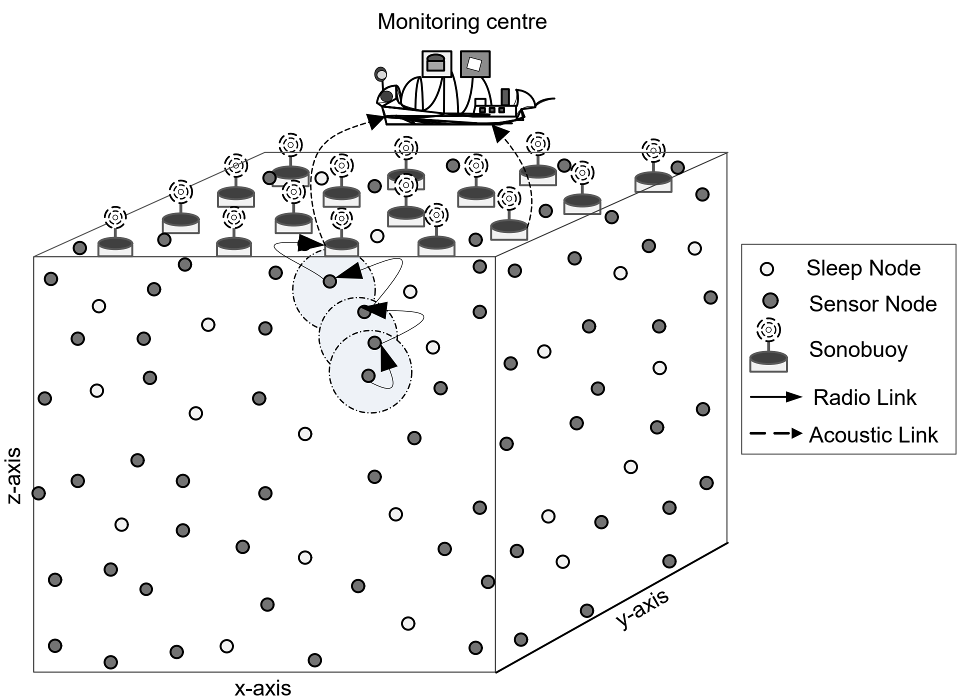
In the category of duty cycling, sensor nodes keep common time references for exchanging the information in order to achieve a certain degree of synchronisation. In the global synchronous scheme, all nodes turn their radio ON or OFF, simultaneously. Though, it is hard to achieve synchronisation without errors in dynamic acoustic environment (Park et al., 2014). An underwater wireless acoustic network-media access control (UWAN-MAC) protocol (Carrano et al., 2014) is an extension of sensor-media access control (S-MAC) (Ye et al., 2002) and time out media access control (T-MAC) (Persis, 2021). In S-MAC, the sensor nodes usually stay in sleep mode and become active after detecting the data packet(s). They exchange signalling information to learn the schedules of their neighbours. This action is intended to schedule wake-up periods at agreed time intervals through the exchange of information. In this way, the S-MAC attains a balance between the energy consumption and network throughput. S-MAC is further optimised in Persis (2021), where active state varies in different cycles. This is to make S-MAC adaptive to different traffic conditions. These mechanisms are extended for the marine environment. However, the node mobility in an underwater environment due to water currents is not considered in UWAN-MAC.

Other scheduling methods focus on synchronous exchange of global information in order to attain the periodic synchronisation. However, the global synchronisation incurs high communication overhead that results in additional energy consumption. This problem is addressed using asynchronous duty cycling schemes. A routing scheme based on the mechanism of region-based adaptiveness is proposed in Li et al. (2021). To maintain the connectivity between neighbouring nodes, wake-up period is overlapped among the neighbouring nodes. Moreover, the number of active, overlapping and total slots are determined using difference set in one cycle (Karim et al., 2021b). Furthermore, this scheme uses cluster-based routing, and guarantees reliable and real-time delivery of data in underwater environment. However, when the nodes are not in the same duty cycle, they can not communicate. Concerning to this problem, a scheme is considered without compromising network connectivity, which selects the possible shortest path to the sink by utilising minimum number of relay nodes (Su et al., 2016). This focuses on energy conservation in IoUTs by modelling wake-up rate of sensor nodes. It is worth noticing that the asynchronous sleep-awake schemes incur high delays.

3 The GOASST

An optimal utilisation of constrained resources, like node's battery in IoUTs, is one of the key parameters in the design of routing algorithm (Khan et al., 2021). To prolong the network lifetime, duty cycling is widely accepted to save the node battery when it is not involved in data communication (Mohd et al., 2022). In this section, a multi-sink architecture is presented along with an asynchronous duty cycling algorithm considering dynamic acoustic environments. Moreover, a synchronous sleep-awake scheme is presented by opting for an opportunistic forwarding mechanism.

Figure 1 Multi-sink network architecture for IoUTs



3.1 System model

It is assumed that in IoUTs, a number of sensor nodes are randomly deployed to sense, monitor, collect and transmit data towards the destination node named as sink (Javaid et al., 2019b). It is assumed that all the underwater sensor nodes are internet-based. Hence, the network is referred to as an IoUT network. Moreover, in order to minimise the delay and the number of hops, a multi-sink architecture is used, as illustrated in Figure 1. The sink nodes receiving the data packets and having infinite energy are regarded as super nodes. They outlast throughout the network lifetime. In addition, the sink nodes have radio and acoustic modems for both land and acoustic communications. Moreover, it is assumed that at the time of deployment each sensor node knows its location in IoUTS.

The network is modelled as an undirected graph $G = (V, E)$, where V is the set of sensor nodes and E represents the wireless links (Jan et al., 2017). Each node in this set is given identical initial energy $E^{initial}$ and communication range R_c. For any pair of nodes (a, b), the wireless link between a and b is $l_{ab}\ \epsilon\ E$, if and only if a and b are in R_c of each other. If P_{ab} is the link reliability between node a and b, then the probability of packet reception by atleast one node in the forwarding set F_s is estimated as:

$$F_s = n_i \epsilon N_k(t) : \exists S_n \epsilon S_s(t) | D(n_i, s_{n^*}) - D(n_k, s_n) > 0. \tag{1}$$

$$P_s = 1 - \prod_{\forall a \epsilon F_s} (1 - P_{ab}). \tag{2}$$

where P_s is the success probability. Equation (2) shows the success probability of one-hop data transmission.

3.2 Neighbourhood discovery

In a real scenario, the sensor nodes are not always awake because this causes premature energy exhaustion. Each node exchanges messages based on its location information atleast once in order to discover and notify the neighbours (Alharbi et al., 2022). The neighbour discovery (ND) message is initially sent by the source node in its transmission range. The receiving nodes then respond to ND message with neighbour acknowledgement (NA) message. Finally, a table consisting of neighbour information is formulated by each node. Hence, each sensor node sends ND message to awake nodes in its vicinity and awake nodes send back NA message. Moreover, each sensor node keeps switching between sleep and awake modes (Zhao et al., 2021). Taking the same duration for active and inactive states, denoted by T in equation (4), the complete working cycle T_c of a sensor node is given in equation (3).

$$T_c = n \times T, \tag{3}$$

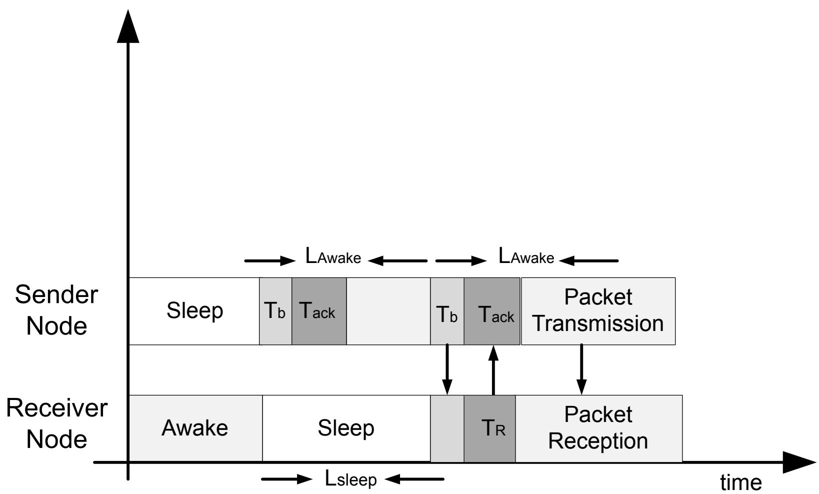
where $n \epsilon R_c$. R_c represents the communication range and v_s represents the transmission speed of a sensor node. T_{ND} and T_{NA} are transmission times of the ND message and NA message, respectively.

$$T = \frac{2R_c}{v_s} + T_{ND} + T_{NA}. \tag{4}$$

In an active state, a sender node broadcasts an ND message to establish connection with the receiving nodes. On receiving an ND message, every node replies with an NA message and the data transmission begins. The goal behind this neighbour discovery is to find eligible awake neighbours for data forwarding (Chenthil and Jayarin, 2021). Atleast one node is required to forward data to the immediate next hop destination and this process continues till the data reaches its final destination.

As shown in Figure 2, when node A intends to transmit data, it switches from inactive to active state and wakes up for a length of time $T_w = T_b + T_{ack}$. T_b is the time taken in transmitting the beacon message to notify the neighbour nodes for data forwarding. Whereas, T_{ack} is the waiting time of the response sent by the neighbour nodes to the sender node A. For successful data forwarding, node A waits for T_{ack} to receive the response from node B (Ramteke et al., 2022). If response is not received, node A goes to inactive mode and comes into an active state after a certain sleep period T_s. After T_s, node A retransmits the beacon message for neighbour discovery and forwards the data packet to the active neighbour node in its forwarding set. In this case, the wake-up time $T'_w = T_b + T_{ack} + T_t$ is the accumulated time taken in sending a beacon message, waiting for response and transmitting the data packet to the neighbour node B.

Figure 2 Illustration of sleep-awake mechanism between a pair of nodes



3.3 Asynchronous mode collaborated with geo-opportunistic routing

To efficiently utilise the node energy, sleep-awake scheduling assisted with geo-opportunistic mechanism avoids meiotic energy consumption and consequently, extends network lifetime (Karim et al., 2021a; Menaga et al., 2021; Hong et al., 2002). Each sensor node wakes up for L_{awake} and retains its sleep mode for a period of length L_{sleep}. Every sensor node has independent sleep-awake schedule that is a plausible assumption as in Kim et al. (2008) because it does not require clock synchronisation between sensor nodes. It helps in saving the rapid energy depletion of nodes. Addition to this, α denotes the total packets generated per unit time (Su et al., 2013).

The wake-up rate is examined to inquire its effect on energy consumption. Then, the length of wake-up period is measured L_{awake} as it affects the amount of energy consumed. It should not be small because in this time period, there might not be enough forwarders in the active state. In equation (5), the objective is minimisation of energy consumption of a sensor node N_s due to E_{beacon} (energy consumed during beacon messages' transmission) and E_{awake} (wake-up period's energy consumption). Equation (6) shows the sum of energy consumed in sending ND for T_{ND} and waiting for response T_w.

$$Minimise\ \alpha \cdot N_s \cdot E_{beacon} + (N - N_s \cdot \alpha) \cdot E_{awake} \tag{5}$$

$$E_{beacon} = E[n_{beacon}] \cdot (T_{ND} \cdot E_{tx} + T_w \cdot E_{idl}) + T_{NA} \cdot E_{rx}. \tag{6}$$

In equation (6), $E[n_{beacon}]$ is the amount of energy consumed in sending an expected number of beacon messages before a successful packet transmission and E_{idl} represents the energy of the node in idle state. For computing E_{awake}, the amount of energy consumed in sending an expected number of beacon messages $E[n_{beacon}]$, wake time period T_{awake} of a sender node and expected length of sleep time $T_{\exp -s}$ are considered in equation (7).

$$\begin{aligned} E_{awake} = {} & E[n_{beacon}] \cdot T_{awake} \cdot \frac{T_{awake}}{T_{awake} + T_{\exp -s}} \\ & + (T_{ND} \cdot E_{tx} + T_w \cdot E_{idl}) + T_{NA} \cdot E_{rx}. \end{aligned} \tag{7}$$

The expected number of beacon messages sent before data transmission depends on T_{awake}. Therefore, the sender node A sends beacon message at T. If receiver node wakes up between T and $T - T_{awake}$, it can receive the beacon message. Considering F_s be the forwarding set selected based on opportunistic routing, then the probability of atleast one awake node can be stated as:

$$P_a = (1 - e^{-\lambda}) \cdot F_s \cdot T_{awake}, \tag{8}$$

where λ is the wake-up rate. Moreover, P_a is used to calculate the expected number of beacon messages sent before data transmission.

$$E[n_{beacon}] = \sum_{n=1}^{N} (1 - P_a) \cdot P_a, \forall n \epsilon N_k. \tag{9}$$

4 Coordinated sink mobility in GOASST

Sink mobility in GOASST is promoted to increase the probability of successful data transmission. Consider a scenario when a mobile sink moves in the vicinity of node N. As mentioned earlier, every node has different length of sleeping time. The following objective function is defined in order to find an optimal sleep-awake duration, denoted by $T^n_{st^*}$, to avoid retransmission.

$$T^n_{st^*} = \text{argmax} U(T^n_{st}), \tag{10}$$

$$U(T^n_{st}) = \sum_{n=i}^{N} (B(T^n_{\exp -s}, T^n_{\min -s})). \tag{11}$$

The expected and minimum sleep times of a node are denoted as $T^n_{\exp-s}$ and $T^n_{\min-s}$, respectively. While B represents the benefit. There is a trade-off between cost associated with minimum sleep time of a node and the benefit associated with the successful data transmission. If a node stays in sleep mode for a short time, energy cost associated with the node staying awake for a long time increases. However, it enhances the chances of receiving the beacon message. To calculate the trade-off cost between minimum sleep time and successful transmission, the following equations are formulated. The probability $P(T^n_{\exp-s}, T^n_{\min-s})$ can be computed as in equation (12),

$$P(T^n_{\exp-s}, T^n_{\min-s}) = \begin{cases} 1, & T^n_{\exp-s} \leq T^n_{\min-s} \\ \frac{T^n_{\exp-s}}{T^n_{\min-s}}, & T^n_{\exp-s} > T^n_{\min-s} \end{cases} \tag{12}$$

Expected sleeping time of a node should meet the constraint stated in equation (13),

$$T^n_{\exp-s} \epsilon [\min DC/V_s - T^n_w, \max DC/V_s - T^n_w], \tag{13}$$

in which, minimum and maximum limits of expected sleep time of the sensor node depend on the distance covered DC by the sink and wake-up period of the sensor node N. V_s represents the maximum transmission speed. Furthermore, the benefit function $B(n)$ can be computed as,

$$B(T^n_{\exp-s}, T^n_{\min-s}) = P(T^n_{\exp-s}, T^n_{\min-s}). \tag{14}$$

Hence, the cost function for the sensor node with different sleep times is:

$$C(T_{\exp-s}) = \beta \times \frac{T^n_{\exp-s}}{T^n_{\min-s}}. \tag{15}$$

β function shows the trade-off between cost associated with minimum sleep and successful data transmission. For a sensor node, β = 1 denotes that the minimum sleeping time benefits in successful transmission. While minimising β in this relation decreases the probability of success and maximises the benefit associated with staying in sleep mode.

5 Linear programming-based mathematical formulation

In this section, the linear programming is discussed to optimise the performance metrics and improve overall performance of network. Linear programming is used to gain the desired outcome of any function or event. Firstly, an objective function is formulated to maximise or minimise a value or an event while considering some constraints. I used linear programming for the identification of feasible regions for performance metrics.

5.1 Energy consumption minimisation

The GOASST energy consumption mechanism mainly depends upon wake-up period E_{awake} and beacon energy E_{beacon}. Therefore, the objective function is given below.

$$Min \sum_{i=1}^{N} E_{Tax}(i) \quad \forall i \epsilon N \tag{16}$$

where E_{Tax} is the energy tax in the network. Initially, the energy consumption in the network is due to the exchange of beacon messages, as shown below,

$$E_{beacon}(ij) = \sum_{i=1}^{N} T_{ND} \times E_{tx} + T_{NA} \times E_{rx} \quad \forall i, j \epsilon N \tag{17}$$

Moreover, E_{tx} is the amount of energy that is consumed in sending the beacon message. While E_{rx} is the amount of energy that is consumed in receiving the beacon message. So, the constraints are formulated as follows.

$$E_{beacon} + E_{awake} < E_{rx} \tag{18}$$

$$T_{awake} \leq T_{sleep}. \tag{19}$$

The accumulated energy consumption in sending beacon messages must not exceed the residual energy of the sender node during transmission [as stated in equation (18)]. Moreover, wake-up period of a node should be less than the sleep period of that node to conserve the energy, as in equation (19).

$$E_{total} = E^{initial} \times N \tag{20}$$

E_{total} is the total energy provided while the initial energy is represented as $E_{initial}$ in equation (20). The energy consumed in all the rounds of simulation is termed as energy tax, which is stated in equation (21). r denotes the round number, $r_{\max}$ denotes the maximum number of rounds.

$$E_{Tax} = \sum_{r=1}^{r_{\max}} (E_{consumed}(r)). \tag{21}$$

Whereas for CSM-GOASST, the same objective function in equation (16) is defined under different linear constraints according to the proposed scenario. The constraints for objective function are given in equations (22) and (23).

$$E_{(tx,rx)} \leq E_i^{initial} \quad \forall i \epsilon N \tag{22}$$

$E_{(tx,rx)}$ is the amount of energy that is required in transmitting and receiving the data packet. The constraint is that this energy should be less than node's initial energy. While on the other hand, equation (23) states that the residual energy of any node should be less than $E_{(tx,rx)}$.

$$E_{(tx,rx)} \geq E_i^{r} \quad \forall i \epsilon N \tag{23}$$

According to equations (24) and (25), the receiver node should be in the transmission range of the sender, i.e., it should be in between $R_{tx}^{\max}$ and $R_{tx}^{\min}$. D_i^j represents the distance from node i to node j.

$$D_i^j \leq R_{tx}^{\max} \quad \forall i, j \epsilon N \tag{24}$$

$$D_i^j \geq R_{tx}^{\min} \quad \forall i, j \epsilon N. \tag{25}$$

$$E_{tx}^{\min} = E_{tx}/L \tag{26}$$

$$E_{rx}^{\min} = E_{rx}/L \tag{27}$$

Graphical analysis: in the first scenario, the transmission range of nodes is kept 250 m. The transmission range is divided into five levels, denoted by L. The division of R_c into different levels helps in observing the energy consumption according to these levels, also depicted in equation (27). According to equation (26), the amount of E_{tx} calculated at L1 and L5 is 2.75 J and 0.85 J, respectively. This energy is calculated by considering different parameters: DR = 16 kbps, packet size = 888 bits, P_{rx} = 0.158 W and P_{tx} = 50 W. Moreover, according to equation (27), the amount of E_{rx} calculated at L1 and L5 is 0.75 J and 0.09 J, respectively.

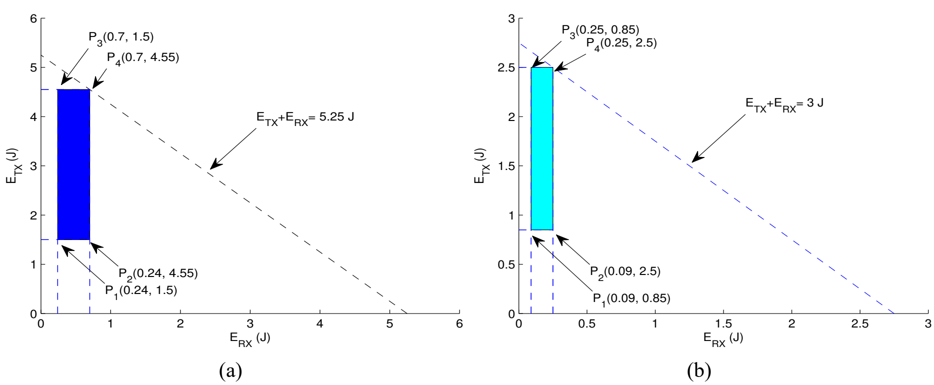
$$0.94 \leq E_{tx} + E_{rx} \leq 2.75 \tag{28}$$

$$0.09 \leq E_{rx} \leq 0.25 \tag{29}$$

$$0.85 \leq E_{tx} \leq 2.5 \tag{30}$$

The bounded regions highlighted in Figure 3 depict the feasible regions. Any point that lies in the bounded region brings a valid solution for energy consumption.

Figure 3 Feasible regions for energy tax, (a) energy tax for GOASST (b) energy tax for CSM-GOASST (see online version for colours)

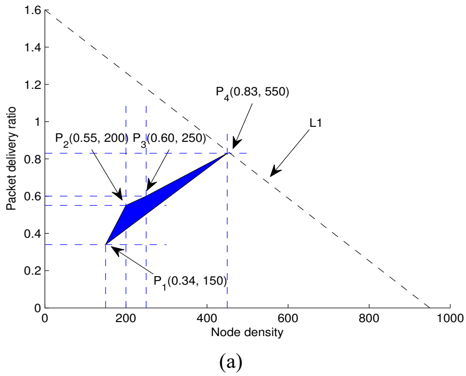


As the next step, each vertex depicted in Figure 3 is tested for CSM-GOASST as:

- at P_1: 0.09 + 0.85 = 0.94 J
- at P_2: 0.09 + 2.5 = 2.59 J
- at P_3: 0.25 + 0.85 = 1.10 J
- at P_4: 0.25 + 2.5 = 2.75 J.

Therefore, by following these methods, valid solutions are obtained, as shown in Figure 3. These solutions make the feasible regions and the values of energy that lie within these regions help to minimise the energy consumption.

Figure 4 Feasible regions for network throughput, (a) PDR for GOASST (b) PDR for CSM-GOAST (see online version for colours)



5.2 *Packet delivery ratio maximisation*

The objective function is to increase the throughput of a network while minimising the energy consumption. The network throughput is the ratio of number of packets sent from source to the number of packets successfully received by the destination. In the proposed network, the multi-hop communication is performed. Moreover, δ is considered as the threshold, which ensures the successful delivery of data packets. It is important to note that the amount of energy required to transmit the packet should be less than the remaining energy of sender node. Furthermore, the distance between sender and receiver should be between $D_{ij}^{\min}$ and $D_{ij}^{\max}$. All the aforementioned constraints are considered for the formulation of objective function, as shown in equation (31).

$$Max \sum_{i=1}^{N} T_p(i); \quad \forall i \epsilon N. \tag{31}$$

where T_p(i) is the network throughput, $T_p(r)$ represents throughput in r rounds, according to equation (32).

$$Max \sum_{r=1}^{r_{\max}} T_p(r) \times P; \quad \forall r \epsilon N, \tag{32}$$

such that:

- C1: $E_{beacon} + E_{awake} \leq E_r$
- C2: $P_{link} \geq \delta$
- C3: $E_{beacon} + E_{awake} \geq E_{th}$.

Where E_r is the total amount of energy, which is required for transmitting and receiving the packet. The objective of throughput maximisation is achieved under constraints C1, C2, and C3. Here C1 and C3 put restrictions on E_r and E_{th} to avoid unnecessary energy consumption. While, C2 ensures the link quality within the threshold before transmitting the data packet. For CSM-GOASST, the linear constraints are defined as:

- C11: $E_{tx,rx} \leq E_r$
- C22: $T_{\exp - s} \leq T_{\min - s}$
- C33: $0 < D_{ij} \leq D_{ij}^{\max}$.

Figure 4 shows the feasible region for maximal throughput. Hence, if the packet delivery at the destination is within the bounded region, then the network has optimised throughput.

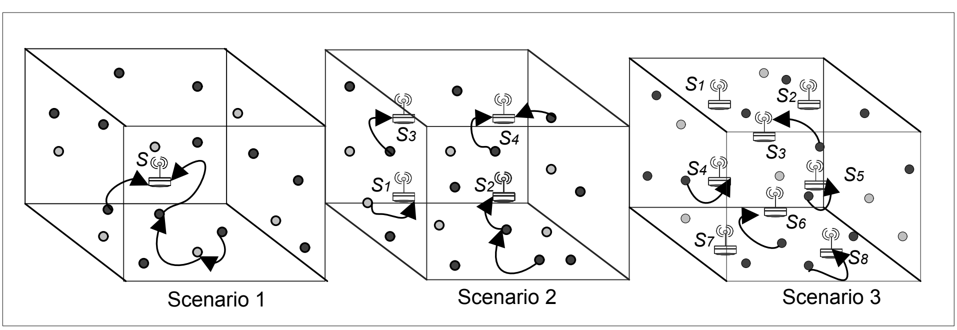
6 Simulation results

In this section, the proposed schemes are evaluated by simulations while considering different parameters: latency, packet delivery ratio (PDR), depth adjustment and energy consumption. The total number of sensor nodes is taken to be 450 while the number of sonobuoys is taken to be 45. The deployment of nodes is random in the field of 1,500 m × 1,500 m × 1,500 m. Moreover, the R_c of nodes and data rate are 250 m and 50 kbps, respectively. Besides, the payload of the data packet is considered 150 bytes. In the awake state, the transmission energy, reception energy and idle state energy are P_t = 2 W, P_r = 0.1 W and P_i = 10 mW, respectively as taken in Coutinho et al. (2014). Further analysis under varying number of sinks in three dimensional field is also presented in this section.

6.1 Topology related results

Simulation analysis has been performed with respect to node density. Simulations for GOASST, CSM-GOASST and GEDAR (Coutinho et al., 2014) are conducted in order to investigate how the proposed schemes perform in the low and high network densities. Forwarding strategies in all the schemes are different and noticing the nodes' behaviours in different network conditions is important. In GOASST, the forwarding set is selected on the basis of residual energy of sensor nodes, whereas, CSM-GOASST selects the nodes based on the advancement towards the destination. Both the schemes follow geo-opportunistic mechanism while selecting the forwarding sets for data forwarding.

Figure 5 Sink positioning in CSM-GOASST



The void nodes decrease with the increase in node density for all forwarding strategies. CSM-GOASST performs better than GOASST and GEDAR (Coutinho et al., 2014) because more number of nodes are in the range of sinks in CSM-GOASST as compared to GOASST and GEDAR. GOASST avoids void holes by selecting the forwarding set with atleast one awake node to receive data packet(s). CSM-GOASST provides maximum coverage by deploying sinks at the optimal positions in the network. Whereas, GEDAR opts depth-based recovery mechanism to tackle the local maximum problem. In addition to this, the total displacement of void nodes is high in sparse network regions. This issue is resolved in CSM-GOASST by placing sinks at optimal positions to reduce the distance between the void nodes and the sinks. Hence, the fraction of void nodes decreases, as shown in Figure 6.

Figure 6 Fraction of void nodes (see online version for colours)

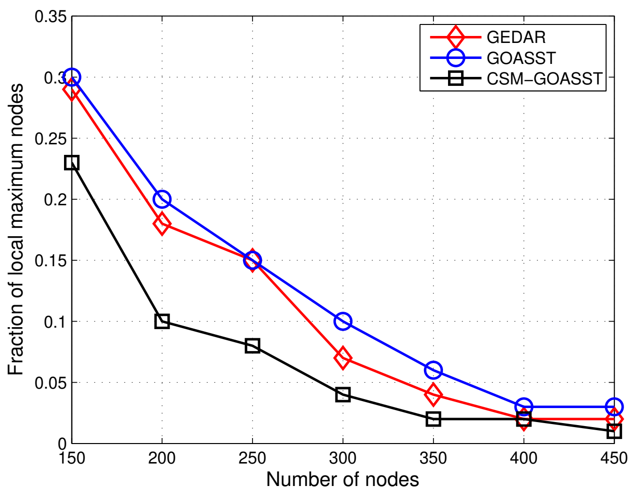
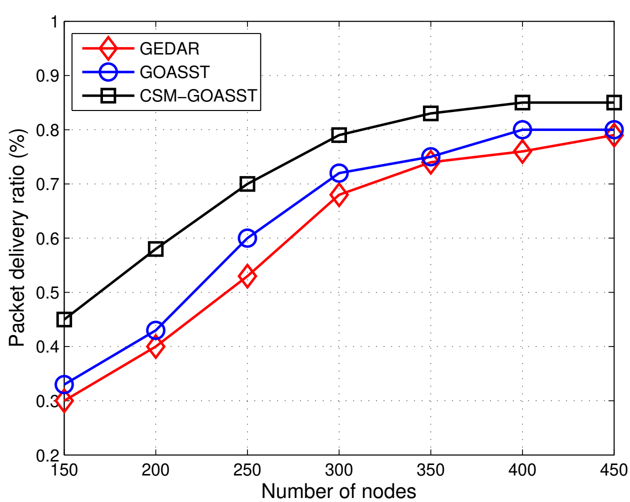


Figure 7 Packet delivery ratio (see online version for colours)

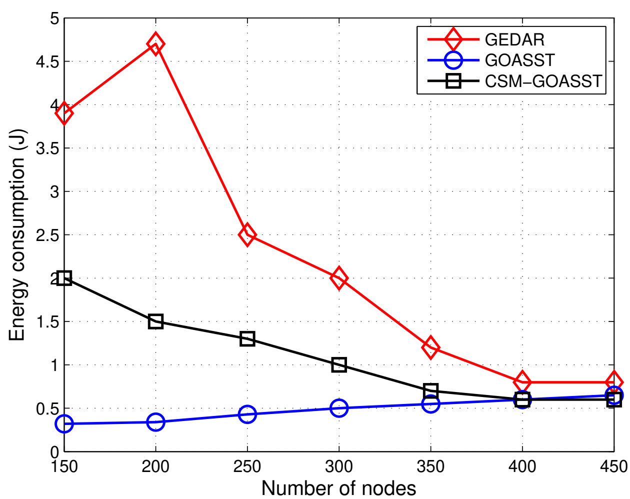


PDR follows the same trend with the change in network density. It increases with the network density for all the schemes. CSM-GOASST outperforms in terms of

PDR because of the maximum coverage over the network assisted with controlled sink mobility. The same performance of GOASST and GEDAR is observed in sparse network regions. The forwarder set selection with atleast one awake node reduces the probability of unsuccessful data transmissions in GOASST. Along with the successful data transmissions, the forwarder set selection with minimum awake nodes reduces the energy consumption. In dense network regions, the number of available awake nodes increases because of high node density while the fraction of void nodes reduces, as corroborated by the results in Figures 6 and 7.

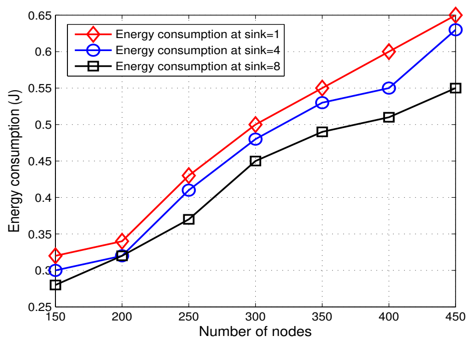
The energy consumption in GEDAR is high for sparse network regions, as shown in Figure 8. Energy expenditure is increased because of the depth adjustment of void nodes in GEDAR. CSM-GOASST also bears high energy consumption in sparse network regions due to high displacement between nodes and sinks. On one hand, when average displacement reduces between the nodes and the sinks because of increased network density, the nodes transmit their data either directly or through hops, which are taken to relay the data towards the destination. While on the other hand, an increase in node density reduces the energy consumption in CSM-GOASST. GOASST exploits sleep-awake scheduling to conserve the energy of the network nodes. It can be observed from Figure 8 that the energy consumption of GOASST is minimum as compared to CSM-GOASST and GEDAR because nodes remain in sleep mode for a long time resulting in low idle listening. When node density is high, the GOASST finds more number of nodes in the forwarder set with the increased awake probability. Ultimately, the probability of successful delivery of data packets is increased at the cost of high energy consumption in dense regions.

Figure 8 Energy consumption (see online version for colours)

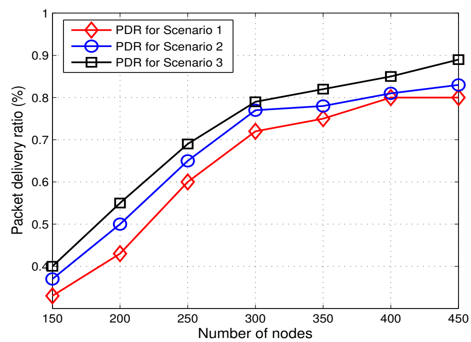


In relation to end-to-end delay, as shown in Figure 10, GOASST bears the largest delay because of probation period dedicated for beacon messages along with the propagation delay caused by forwarder to sink packet propagation. End-to-end delay increases with the node density for all forwarding strategies. GEDAR and GOASST follow opportunistic routing to improve the data delivery, but the selection of forwarder set instead of a single forwarder node causes high delays. CSM-GOASST forwards data packets based on the minimum number of hops as compared to GOASST and GEDAR; thus, it bears the least end-to-end delay.

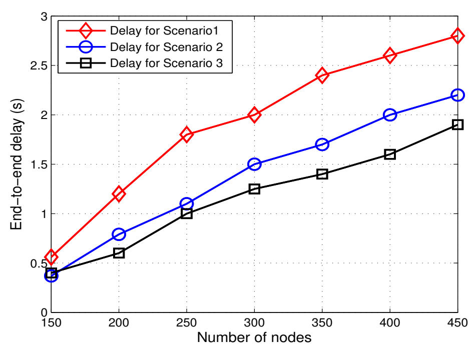
Figure 9 Performance parameters of CSM-GOASST, (a) energy consumption for varying number of sinks (b) PDR under varying number of sinks (c) end to end delay under varying number of sinks (see online version for colours)



(a)



(b)



(c)

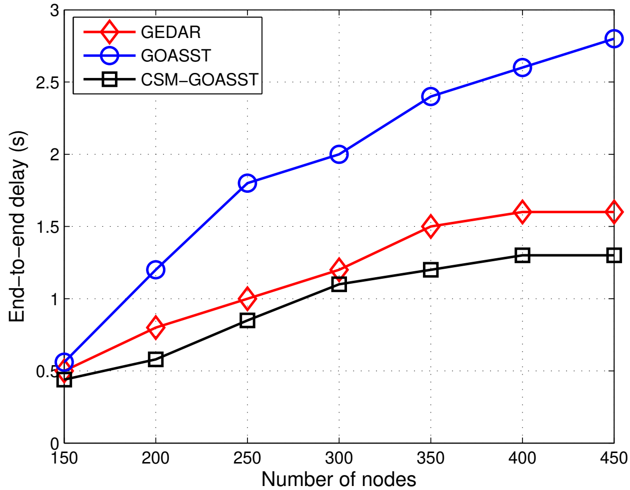
Table 1 The performance comparison of the proposed techniques with GEDAR

Schemes	*PDR*	*Energy tax*	*End-to-end delay*
GOASST	4% improved	50% more efficient	40% increased
CSM-GOASST	5% improved	15% more efficient	28% reduced

6.2 Sink utilisation in CSM-GOASST

An analysis with different number of sinks under varying network density is carried out (as shown in Figure 5). It is investigated that how network scalability gets affected by different number of sinks at different positions in the network. With a single sink placed at the centre of the network, $d_{sink-centre} = \frac{\sqrt{d^2+d^2_{sink-surface}}}{2}$, the nodes near the sink forward data packets towards it, instead of surface sinks. The utilisation of this sink increases because nodes below the d_{centre} depth region forward their data to it.

Figure 10 Average delay (see online version for colours)



In the second scenario, four sinks are deployed in order to provide maximum coverage in the network, as shown in Table 2. The utilisation ratio of a single sink is now divided into four sinks. Figures 9(a), 9(b) and 9(c) show the network performance as evidence that the energy consumption reduces due to the usage of less number of hops in forwarding the data to the sinks. Consequently, it reduces the end-to-end delay.

Table 2 Sink position scenarios in CSM-GOASST

Sink	*Coordinates*
	Scenario 1
S	$(x + 750, y + 750, z + 750)$
	Scenario 2
S_1	$(x + 500, y + 500, z + 1{,}000)$
S_2	$(x + 1{,}000, y + 500, z + 1{,}000)$
S_3	$(x + 500, y + 1{,}000, z + 500)$
S_4	$(x + 1{,}000, y + 1{,}000, z + 500)$
	Scenario 3
$S1$	$(x + 250, y + 250, z + 1{,}250)$
S_2	$(x + 1{,}250, y + 250, z + 1{,}250)$
S_3	$(x + 750, y + 1{,}000, z + 1{,}000)$
S_4	$(x + 250, y + 750, z + 750)$
S_5	$(x + 1{,}250, y + 750, z + 750)$
S_6	$(x + 750, y + 500, z + 500)$
S_7	$(x + 250, y + 250, z + 250)$
S_8	$(x + 1{,}250, y + 250, z + 250)$

In the third scenario, eight sinks are deployed. The coordinates of deployed sinks are enlisted in Table 2 (scenario 3). As the number of sinks increases, the number of paths available to forward the data towards the surface sinks also increases. Taking network conditions into account, the placement of sinks at the optimal distance provides maximum network coverage. The controlled sink mobility is introduced to solve connectivity problems. The major objective is to provide maximum connectivity among the nodes. The results show that multiple sinks deployed in the field for data collection restrict the bottleneck created at the surface sinks. Using multiple hops to relay data towards the surface sinks results in drastic energy consumption by the nodes. Thus, multi-sink mechanism performs better in high traffic scenarios and in large networks.

7 Performance trade-off

In the proposed schemes, there is a trade-off between performance parameters. It exhibits that certain performance parameters are improved at the cost of a particular parameter. GOASST scheme ensured energy efficiency at the cost of increased end-to-end delay. Whereas, CSM-GOASST ensured reduction in the end-to-end delay while compromising the energy cost in sparse network regions. Performance of GOASST scheme under coordinated sink mobility is given in Table 1. This trade-off is presented in comparison with GEDAR routing scheme in percentage form. The energy efficiency and end-to-end delay of GOASST are increased by 50%, and 40%, respectively. It is observed that CSM-GOASST is 15% more efficient in terms of energy consumption. Whereas, the end-to-end delay is reduced up to 28% as compared to GEDAR.

8 Conclusions and future work

The routing schemes proposed in the underlying work are GOASST and CSM-GOASST. Both techniques focus on energy efficiency and reliable data delivery. Modelling of wake-up rate and wake-up period for energy efficiency in IoUTs is performed. The collaborative design of sleep-awake scheduling with geo-opportunistic routing provides link reliability and consequently, high ratio of packet delivery is achieved. The simulation results show the performance of the proposed schemes. Additional overhead is minimised by opting asynchronous sleep-awake scheduling. The performance of GOASST and CSM-GOASST schemes in multi-sink architecture is evaluated, which shows that the CSM-GOASST benefits in achieving the reduced average delay. Furthermore, mathematical modelling is carried out to find feasible solutions in order to minimise energy consumption and end-to-end delay. Through extensive simulations, performance of the proposed techniques for energy efficiency in IoUTs along with reduced end-to-end delay is verified.

In the future, node mobility in the proposed scenarios will be considered to inquire its influence on network performance.

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