

# Energy-Efficient Geographic Routing with Obstacle Avoidance in Wireless Sensor Networks

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## Abstract

Wireless sensor networks (WSNs) are essential in environmental, industrial, and urban monitoring applications. However, in hostile environments where communication is hampered by physical obstacles, traditional geographic routing protocols suffer from significant performance degradation. This paper presents OAGF (Obstacle-Aware Greedy Forwarding), a geographic routing protocol capable of obstacle avoidance while optimizing energy consumption and latency. OAGF combines an adaptation of Greedy Forwarding with mechanisms for obstacle detection, alternative route selection, and residual energy consideration. Simulations under OMNeT++/INET 4.4 demonstrate that OAGF reduces latency by an average of 31%, total energy consumption by 38%, and improves delivery rates by 7% compared to GARL and GEAR. These results show that OAGF is a robust and efficient approach for RCSF deployments in complex environments.

## Keywords

Wireless Sensor Networks, Geographic Routing, Obstacle Avoidance, Energy Optimization

## 1. Introduction

Wireless sensor networks (WSNs) are a technological pillar of the Internet of Things (IoT) for the collection and transmission of environmental data [1] [2]. Thanks to their low cost, flexibility, and autonomy, they are deployed to monitor physical phenomena such as temperature, humidity, or the detection of critical events.

However, in real-world environments, the presence of obstacles (buildings, rocks, dense vegetation, metal structures, etc.) limits radio range and creates communication gaps, leading to transmission failures, costly retransmissions, and excessive energy consumption [3]. Conventional geographic routing protocols, such as GPSR [4] or GOAFR [5], although effective in open environments, often fail in the face of these constraints.

The motivation for this work therefore lies in the design of an intelligent routing protocol capable of maintaining stable performance in a constrained environment, integrating obstacle awareness and energy management.

Our main contributions are :

- Adapting the *Greedy Forwarding* strategy to include obstacle detection and residual energy.
- The introduction of a local adaptive recovery mechanism in case of blocking.
- A multi-criteria mathematical model combining latency, energy, and reliability.
- A detailed experimental evaluation under OMNeT++ and comparison with GARL and GEAR.

## 2. State of Art

Geographic routing relies on the position of nodes to route data without a global routing table [4]. This approach is efficient and scalable, but it becomes limited in the presence of obstacles or energy constraints. The main families of protocols can be grouped into four categories: classic, topological, intelligent, and recent deep learning-based protocols.

### 2.1. Classic Protocols

The first approaches rely on geographical distance to choose the next hop.

GPSR (Greedy Perimeter Stateless Routing) [4] combines a *Greedy* mode to transmit to the neighbor closest to the destination and a *Perimeter* mode to bypass blocked areas. It is simple and effective but fails in the presence of physical obstacles or coverage gaps and ignores energy consumption.

GOAFR (Greedy Other Adaptive Face Routing) [5] improves on GPSR by limiting detours when bypassing but remains sensitive to mobile obstacles and does not take energy constraints into account.

These protocols favor the shortest distance without considering link reliability or the residual energy of the nodes.

### 2.2. Topological Approaches

Topological protocols integrate communication graph structure to improve routing stability.

CLDP (Cross-Link Detection Protocol) [6] creates a planar topology by removing redundant links to avoid loops but generates an overload of control messages.

GLIDER (Geographic Layered Routing) [7] combines position and connectiv-

ity information for better fault tolerance, at the cost of increased complexity and significant energy consumption.

Ant-based routing approaches such as AntHocNet [8] use bio-inspired heuristics to improve path discovery and adaptivity in dynamic networks.

These approaches enhance structural robustness but are costly to maintain in dense or energy-limited networks.

### 2.3. Intelligent Protocols

Recent protocols incorporate adaptive mechanisms based on energy and learning.

GEAR (Geographic and Energy Aware Routing) [9] balances distance and energy consumption, extending the network's lifespan, but remains ineffective in the face of obstacles.

GARL (Geographic Adaptive Routing with Learning) [10] adapts its decisions based on past experiences through reinforcement learning, but its convergence is slow and resource intensive.

HGSR [11] and EHGSR [12] bypass coverage holes by selecting alternative geometric paths, with good performance in static networks but reduced efficiency in dynamic environments.

In addition, MGR [13] extends geographic routing concepts to underwater WSNs, highlighting the versatility of such methods.

These protocols represent progress, but none of them simultaneously address physical obstacles, latency, and energy consumption.

### 2.4. Recent Work Based on Deep Learning

The rise of artificial intelligence has given rise to more autonomous approaches. DeepRL-Routing [14] uses *deep reinforcement learning* to optimize route selection based on network conditions (energy, link quality, distance).

E2DRL-WSN [15] applies distributed learning to improve reliability and energy efficiency.

These solutions offer very good performance, but their computational complexity and memory requirements make them difficult to deploy on sensors with limited resources.

In summary:

- Conventional and topological protocols perform well in open environments but fail when obstacles disrupt connectivity.
- Intelligent protocols improve energy management, but do not effectively solve obstacle avoidance problems.
- Deep learning approaches are promising, but still not well suited to real-world low-capacity wireless sensor networks (WSNs), as they often require models with high memory and computation footprints that exceed typical sensor node capabilities.

Faced with these limitations, the OAGF (Obstacle-Aware Greedy Forwarding) protocol aims to combine simplicity, energy efficiency, and intelligent obstacle

avoidance for more robust and balanced geographic routing.

### 3. Problem Statement and Modeling

#### 3.1. Formulation

Let us consider a graph  $G = (V, E)$  representing the network, with  $V$  the set of nodes and  $E$  the links.

Each link  $(i, j) \in E$  has a cost  $c(i, j)$  depending on distance, link quality, and energy consumption.

Obstacles are modeled by a set  $O = \{o_1, o_2, \dots, o_n\}$  that prevents direct communication between two nodes if the segment  $(i, j) \cap o_k \neq \emptyset$ .

The objective is to determine a path  $P^*$  between the source  $s$  and the destination  $d$  that:

$$\min_p f(P) = \alpha \sum c(i, j) + \beta \sum E(i, j) - \gamma \prod R(i, j) \quad (1)$$

where:

- $\alpha, \beta, \gamma$  are normalized weights,
- $E(i, j) = E_{elec} + \epsilon d(i, j)^2$ ,
- $R(i, j)$  is the probability of link success.

#### 3.2. Assumptions

- Each node knows its position (via GPS or relative location).
- Obstacles are detected locally via RSSI signals or periodic exchanges.
- Nodes have limited energy (initially 100 J).

### 4. Proposed Algorithm: Obstacle-Aware Greedy Forwarding (OAGF)

#### 4.1. Principle

OAGF combines Greedy Forwarding with multi-criteria decision-making (distance, energy, obstacles).

When a node cannot progress, a local recovery procedure is activated to bypass the obstacle.

#### 4.2. Main Steps

1) Selection of candidate neighbor: among the neighbors closest to the destination, the one that minimizes

$$Score(w) = \alpha \cdot d(w, d) + \frac{\beta}{E_{res}(w)} + \delta \cdot ObstacleCost(w) \quad (2)$$

where  $ObstacleCost(w) = 0$  if there are no obstacles, otherwise penalty = 1.

2) Update the route and send the packet.

3) Recovery: if no valid neighbor is found, a detour mechanism is initiated (simplified Face Routing). In practice, this recovery phase behaves as a lightweight Perimeter mode similar to GPSR, where the right-hand rule is applied to follow

the obstacle boundary until a node closer to the destination than the entry point is reached.

### 4.3. Pseudocode of OAGF

1. if  $u == d$ :
2.     DELIVER(packet); return
3.      $CAND \leftarrow \{v \in N(u) \mid d(v,d) < d(u,d) \wedge NON\_BLOCKED(u,v)\}$
4.     if  $CAND \neq \emptyset$ :
5.         for each  $v \in CAND$ :
6.              $s(v) \leftarrow \alpha \cdot DIST(v,d)_{norm} + \beta \cdot ENERGY(u,v)_{norm} + \gamma \cdot OBSTACLE\_COST(u,v)_{norm}$
7.              $w \leftarrow \text{argmin}_v s(v)$
8.             FORWARD(packet, w); return
9.     else:
10.     // LOCAL RECOVERY (Simplified Face / Perimeter mode)
11.     if package.recovery\_mode == FALSE:
12.         package.recovery\_mode  $\leftarrow$  TRUE
13.         package.anchor  $\leftarrow$  u     // entry point of the recovery phase
14.          $w \leftarrow NEXT\_NEIGHBOR\_PERIMETER(u, d)$      // right-hand rule
15.     if  $w \neq \perp$ :
16.         FORWARD(packet, w); return
17.     else:
18.          $w \leftarrow NEXT\_PERIMETER\_NEIGHBOR(u, d)$
19.         if  $w \neq \perp \wedge d(w,d) < d(\text{package.anchor},d)$ : // obstacle has been bypassed
20.         package.recovery\_mode  $\leftarrow$  FALSE
21.     if  $w = \perp$ :
22.         // Option: limited backtracking or NACK
23.         DROP(packet)     // or SEND\_NACK(source)

Lines 1 to 2 verify the destination. If the current node is the final node, the packet is delivered immediately and routing stops.

Lines 3 to 8 describe the Greedy mode routing phase. The node selects from among its neighbors those that are closest to the destination and whose links are not blocked. Each neighbor is evaluated according to a multi-criteria score combining distance to the destination, energy consumption, and proximity to obstacles. The neighbor with the lowest score is chosen for transmission.

Lines 9 to 10 signal the switch to the recovery phase when no valid neighbors are available. This step aims to bypass obstacles that prevent direct progress.

Lines 11 to 16 initiate recovery mode (Face/Perimeter). The packet enters recovery mode, an anchor point is defined, and the protocol applies the right-hand rule to follow the contour of the obstacle until it finds a clear path.

Lines 17 to 20 manage the continuation of the detour. If a neighbor allows progress while moving closer to the destination relative to the anchor point, this means that the obstacle has been passed: recovery mode is then disabled and routing returns to normal Greedy mode.

Finally, lines 21 to 23 define failure management. If no neighbor is available, the protocol can attempt a limited backtracking or send a NACK to the source. As a last resort, the packet is dropped (DROP).

## 5. Experimental Evaluation

### 5.1. Simulation Parameters

The simulation parameters used in this study are summarized in **Table 1**.

**Table 1.** Simulation parameter.

Parameter	Value
Simulator	OMNeT++ 5.7 + INET 4.4
Surface	100 m × 100 m
Nodes	100 - 500
Obstacles	0 - 20 (rectangular shapes 10 × 10 m)
Radio range	20 m
Initial energy	100 J
Packet size	512 bytes
Protocols compared	OAGF, GARL, GEAR
Simulation duration	200 s
Transmission frequency	1 packet/s

### 5.2. Performance Indicator

- Average latency (ms)

For a packet  $p$  routed along the path  $P = \{1, \dots, H_p\}$  (with  $H_p$  hops), the end-to-end latency is the sum of the delays per hop:

$$L_p = \sum_{h=1}^{H_p} (t_{tx,h} + t_{prop,h} + t_{proc,h} + t_{queue,h}). \quad (3)$$

$t_{tx}$  : transmission delay (size/bitrate, including any MAC backoffs)

$t_{prop}$  : propagation ( $\approx d/c$ , often negligible in WSN)

$t_{proc}$  : processing (protocol stack)

$t_{queue}$  : queueing (MAC, radio interface)

The average latency over a set  $\mathcal{D}$  of delivered packets (size  $|\mathcal{D}|$ ):

$$\bar{L} = \frac{1}{|\mathcal{D}|} \sum_{p \in \mathcal{D}} L_p \text{ (en ms)} \quad (4)$$

Assuming independent and identically distributed hops with average delay  $\mu_c$ , then

$\mathbb{E}[L_p] \approx \mu_l \mathbb{E}[H_p]$ , which directly links the average latency to the average number of hops.

- Total energy consumption (J)

For a packet of  $k$  bits transmitted over a link of distance  $d$  :

$$E_{tx}(k, d) = E_{elec}k + \epsilon_{amp}kd^n, E_{rx}(k) = E_{elec}k,$$

$E_{elec}$  : electronic cost/bit (e.g., 50 nJ/bit)

$\epsilon_{amp}$  : amplification cost (e.g., 100 pJ/bit/m<sup>2</sup>)

$n \in [2, 4]$  : path loss exponent (2 free space, >2 in shadowing/fading)

Add listening/standby and retransmission components:

$$E_{idle} = P_{idle} \cdot T_{idle}, E_{cca} = P_{rx} \cdot T_{cca}, E_{retx} = r \cdot E_{tx}(k, d)$$

where  $r$  is the number of retransmissions.

Total network energy over the simulation period  $T$  :

$$E_{tot} = \sum_{u \in V} \left( \sum_{tx \text{ de } u} E_{tx} + \sum_{rx \text{ de } u} E_{rx} + E_{idle}(u) + E_{cca}(u) \right) \quad (5)$$

- Delivery rate (%)

$$PDR = \frac{N_{livres}}{N_{emis}} \times 100\% \quad (6)$$

PDR: Packet Delivery Ratio

$N_{livres}$  : Number of packets delivered

$N_{emis}$  : Number of packets sent

## 6. Results and Discussion

### 6.1. Average Latency

The curve “**Figure 1**” shows that average latency increases with the number of obstacles for all three protocols (GEAR, GARL, and OAGF).

- In the absence of obstacles (0), OAGF reaches 95 ms, compared to 118 ms for GEAR and 110 ms for GARL.
- With 20 obstacles, latency rises to 185 ms (GEAR), 175 ms (GARL), and 126 ms (OAGF).

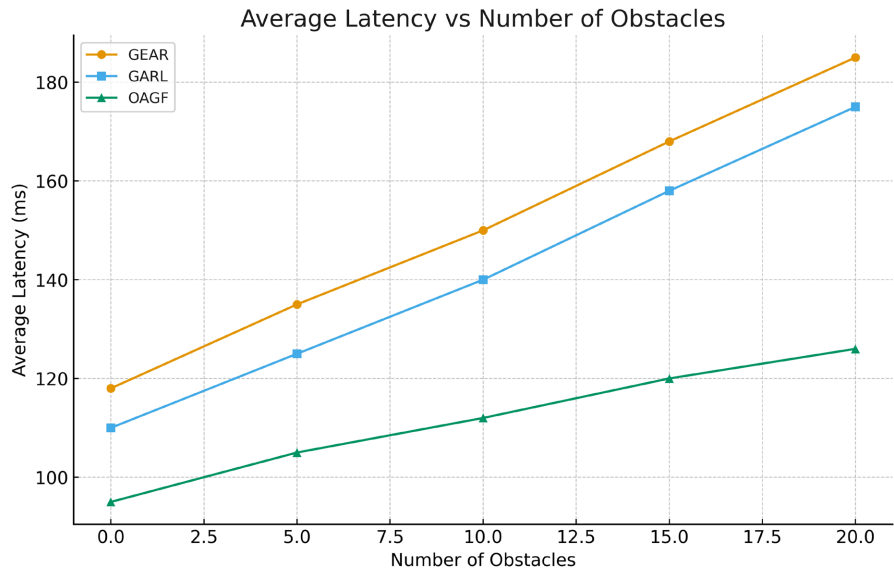
The increase in latency with the number of obstacles is an expected phenomenon, as obstacles cause detours and additional retransmissions.

However, OAGF shows a much slower increase in latency, with an average reduction of 31% compared to GEAR and 24% compared to GARL.

This improvement can be explained by:

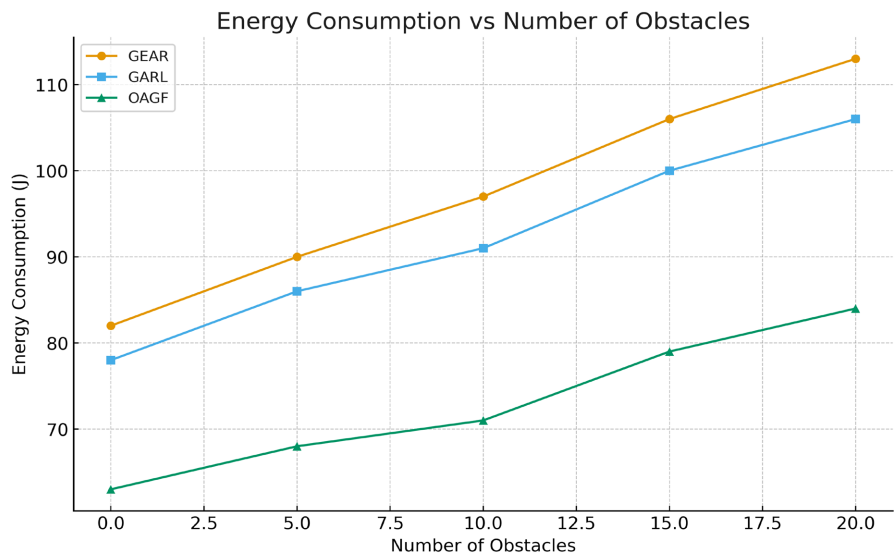
- adaptive neighbor selection, which minimizes detours around obstacles;
- an energy cost function that avoids overloaded nodes by preferring neighbors with sufficient residual energy; this limits local congestion, packet loss, and retransmissions due to depleted nodes, which in turn reduces end-to-end latency;
- a local recovery mechanism that prevents repeated routing failures.

Thus, OAGF ensures faster end-to-end data transmission, even in environments cluttered with obstacles a major advantage for time-sensitive IoT applications (real-time monitoring, industrial automation, etc.).



**Figure 1.** Average latency vs number of obstacles.

## 6.2. Energy Consumption



**Figure 2.** Energy consumption vs number of obstacles.

As shown in “**Figure 2**”, the total energy consumption increases with obstacle density for all protocols.

- With 0 obstacles, consumption is 63 J for OAGF, compared to 82 J for GEAR and 78 J for GARL.
- With 20 obstacles, OAGF consumes 84 J, while GEAR and GARL reach 113 J and 106 J, respectively.

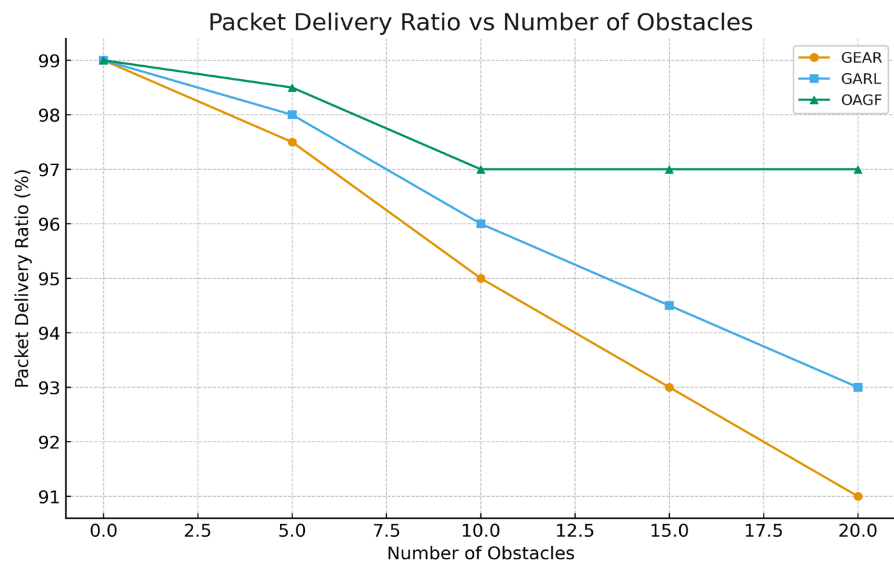
The presence of obstacles results in longer paths, more intermediate hops, and more retransmissions, thereby increasing energy expenditure. Nevertheless, OAGF maintains significantly lower consumption (approximately 38% average reduction).

This efficiency stems from:

- the energy-sensitive routing criterion, which favors nodes with higher residual energy;
- shorter bypass paths, reducing the total distance traveled;
- and a lower retransmission rate thanks to better link quality estimation.

As a result, OAGF significantly extends the lifetime of the network, making it particularly suitable for resource-constrained IoT networks, such as environmental monitoring systems or smart agriculture.

### 6.3. Success Rate



**Figure 3.** Packet delivery ratio vs number of obstacles.

All protocols “**Figure 3**” show a gradual decline in delivery rate as obstacles increase, but OAGF maintains the best results.

- At 0 obstacles, all protocols achieve approximately 99%.
- At 20 obstacles, the PDR drops to 91% (GEAR) and 93% (GARL), but remains at 97% for OAGF.

Obstacles cause packet loss due to link breaks or retransmission failures.

However, OAGF maintains a high and stable PDR thanks to:

- its obstacle detection and bypass mechanism, which guarantees connectivity;
- its balanced energy management, preventing premature node discharge;
- and its adaptive recovery procedures, limiting packet loss in blocking areas.

Thus, OAGF demonstrates high robustness and increased reliability, ensuring continuity of data flow even in difficult communication environments.

The three curves show that OAGF effectively balances the three key indicators: latency, energy, and reliability.

It outperforms GEAR and GARL across all metrics thanks to its multi-criteria decision model that integrates:

- distance to destination,

- remaining energy,
- and obstacle awareness (weighted by  $\gamma$ ).

This combination gives OAGF better network stability, efficiency, and longevity, confirming its relevance for real-world IoT and WSN applications deployed in complex or physically constrained environments.

## 7. Conclusion and Future Work

This article has presented OAGF, a robust and energy-efficient geographic routing protocol for wireless sensor networks (WSNs) deployed in obstacle-filled environments.

The results show significant gains:  $-31\%$  latency,  $-38\%$  energy consumption, and  $+7\%$  reliability compared to recent GARL and GEAR protocols.

Future prospects include:

- The integration of node mobility and dynamic obstacles;
- The exploration of lightweight Deep Reinforcement Learning strategies to improve route selection, for example by using compact models or offloading training to more powerful nodes so as not to overload resource-constrained sensors;
- Adding energy security mechanisms against flooding or black-hole attacks.

OAGF thus represents a promising advance for critical IoT applications, including environmental monitoring, disaster management, and precision agriculture.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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