A Survey on 3D Geographical Routing Protocols in Ad Hoc and Sensor Networks

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Abstract

Geographical routing represents a significant field of study within wireless networks, where the establishment of routes relies on the known positions of wireless nodes. These positions can either be precise physical locations or virtual representations. Numerous geographical routing protocols, utilizing greedy and face routing methodologies, have been developed for two-dimensional networks; however, these protocols may prove inadequate in three-dimensional environments such as hilly terrains, airborne networks, subterranean networks, and underwater networks, among others. This paper aims to explore the research challenges and issues associated with geographical routing on three-dimensional surfaces. The routing techniques in question face various difficulties, including energy efficiency, localization, mobility, load balancing, routing stretch, and void node problems. A literature review has been conducted to address these concerns. Furthermore, this paper discusses recent research findings related to geographical routing, with a primary emphasis on the techniques, issues, and challenges pertinent to three-dimensional geographic routing.
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Keywords: 3D geographical routing , Virtual coordinates , High-genus structure ,Sensor networks.

Introduction

A wireless ad hoc network is composed of either stationary or mobile nodes that interact through wireless mediums such as Bluetooth, Wi-Fi, ZigBee, and UWB [1]. These nodes exhibit self-organizing capabilities and operate in a multi-hop manner. The versatility of wireless networks has led to their widespread application across various fields, including military operations, healthcare, environmental monitoring, entertainment, smart cities, smart homes, smart agriculture, and smart grids. Depending on their geographical structure, wireless networks can be classified into four primary categories namely terrestrial wireless networks , airborne networks ,Underwater wireless networks and underground wireless networks

Terrestrial Wireless Networks

In terrestrial wireless networks, the wireless nodes are confined to a specific area. Common examples of these networks include mobile ad hoc networks (MANETs), vehicular ad hoc networks (VANETs), wireless mesh networks (WMNs), and wireless sensor networks (WSNs). MANETs consist of mobile nodes, resulting in frequently changing communication links with other nodes. These networks can be established as needed over a limited range and for a short duration, such as during emergencies, disaster recovery, relief operations, and military applications [2,3]. VANETs are based on the principles of MANETs but are specifically designed for vehicles, allowing them to communicate effectively.

VANETs are based on the principles of MANETs, specifically tailored for vehicles as nodes, enabling communication among vehicles through the support of roadside infrastructure. Additionally, VANETs exhibit predictable movement patterns, typically along roadways, and vehicles demonstrate a higher degree of mobility compared to those in MANETs. Following this, we will provide a concise overview of WMNs and WSNs, which are prevalent in terrestrial networks. WMNs integrate both ad hoc and infrastructure elements, comprising mesh routers, mesh clients, and gateways. These networks find applications in various scenarios, including battlefield surveillance, oil rigs, tunnels, real-time telemetry for racing cars, and building automation. Another relevant network type is WSN, which consists of numerous sensor nodes designed to monitor physical or environmental parameters such as pressure, temperature, humidity, moisture, noise levels, and mechanical stress. These nodes possess the ability to sense, process, and gather data from their surroundings transmitting this information to end users. The nature of sensor networks can be either ad hoc or structured, depending on the specific application. WSN applications encompass habitat monitoring, agricultural oversight, health monitoring, forest fire detection, and flood detection.

Airborne network is a type of wireless ad hoc network where communicating nodes are deployed with the aerial vehicles [4]. Usually, nodes fly in the air, so it is called as flying ad hoc network (FANET). The underground wireless networks consist of wireless nodes that operate below the ground surface. Such networks are different from the terrestrial networks in term of communication medium e.g. soil, rocks and water where wireless communication techniques for terrestrial networks may not work well [5].

Underwater network applications like ocean environment monitoring, ocean mapping, water quality monitoring, fish farm management, oil/mineral exploration, marine life monitoring, disaster prevention, assisted navigation and tracking etc., requires nodes to be deployed inside the water [6].

Overview of issues and challenges

We have examined the various categories of wireless ad hoc and sensor networks, wherein autonomous nodes engage in communication within a wireless environment. These networks are expected to deliver efficient, cost-effective, and resilient processing and communication capabilities. While the aforementioned wireless networks differ in their applications and operational contexts, they share several common characteristics. Primarily, these networks are typically multi-hop in nature, meaning that nodes may not have a direct connection to the destination or sink node. Consequently, there is a necessity for an appropriate routing scheme to facilitate data transfer. Additionally, networks such as MANET, VANET, FANET, mobile sensor networks, and underwater networks exhibit mobility. Furthermore, certain networks, including underground networks, underwater networks, networks in hilly regions, high-rise building networks, and flying ad hoc networks, possess a three-dimensional structure. Moreover, wireless nodes are powered by batteries, and they are susceptible to security threats. Therefore, it is imperative to address these concerns prior to the design of any protocol. Typically, wireless nodes in these networks operate in a multi-hop manner, necessitating that messages traverse through a series of intermediate nodes. As a result, an effective routing protocol is essential for data transmission. Traditional wireless ad hoc routing protocols can be broadly classified into two categories: proactive and reactive. Proactive routing protocols are table-driven, with each node maintaining an updated routing table and periodically broadcasting routing information to refresh the tables of neighboring nodes. This approach, however, experiences high storage and communication costs. Conversely, reactive routing protocols require the sender node to establish a route prior to data transmission, which can lead to increased communication costs and initial delays associated with route establishment. It is important to note that wireless nodes are typically battery-operated and possess limited memory capacity. Traditional proactive and reactive routing protocols are inadequate for certain applications, making geographical routing a more effective alternative. Geographical routing protocols do not require the maintenance of a routing table and are resilient to changes in network topology. Moreover, these protocols eliminate initial routing delays. When the source node is aware of the destination or sink node's location, it can transmit data directly. In Cadger et al. [7] have addressed routing challenges within a two-dimensional geographic context. Additionally, Huang et al. [8] provided a comprehensive review of three-dimensional geographical routing in wireless mobile ad hoc and sensor networks. This paper expands upon the existing literature on 3D geographical routing techniques and incorporates recent findings. We analyze the advantages and disadvantages of current 3D geographical routing protocols, focusing on aspects such as routing stretch, the local-minimum/dead-end problem, obstacle and void management, energy efficiency, load balancing, mobility, virtual coordinate systems, and localization challenges.

Geographical routing

Geographical routing protocols utilize the location information of nodes, whether physical or virtual. Therefore, the initial step involves acquiring these coordinates. Physical coordinates can be determined through the use of the global positioning system (GPS) or a location service protocol [9-11]. Conversely, several researchers have introduced effective methods [12-14] for generating virtual coordinates. These geographical routing methods are also referred to as position-based, geometric, geographic, location-based, or directional routing. An example of geographical routing in mobile ad hoc networks (MANET) is location-aided routing (LAR)[15]. These methods operate under certain assumptions, including: - Nodes possess knowledge of their own geographical location and that of their one-hop neighbors. Nodes are aware of the geographical location or region of the destination. Each packet is capable of containing a limited amount of routing information, specifically O(1). Geographical routing protocols can be classified into two main categories: greedy forwarding and face routing.

Greedy Forwarding

The greedy forwarding method involves directing packets to the neighboring node that is nearest to the destination at each step. This routing strategy is straightforward to comprehend and implement, making it highly effective for the route discovery process. A typical representation of the greedy forwarding technique is illustrated in Figure 1, where S and D denote the source and destination nodes, respectively, while other nodes may serve as intermediaries. Each node is assigned specific (x, y) coordinates, and the variable d signifies the Euclidean distance to the destination node D. The circles shaded in sky color represent the communication range, assumed to be 50 units, of the respective central node. In this scenario, node S has three neighboring nodes (n2, n3, n4) within its communication range; however, n3 is the closest to D, making it the next node for packet forwarding. This process continues with nodes (n3, n6, n9, n11) executing similar actions until the packet successfully arrives at destination D. There are instances when a packet may reach a node that lacks a suitable forwarding option, potentially due to a network hole or node failure. This situation can prevent the packet from reaching its destination and is referred to as the local minimum, dead-node, or dead-end problem. Consequently, greedy routing does not ensure a viable path, even when alternative routing options exist. Variants of the greedy approach include geographic landmark routing (GLR), greedy distributed spanning tree routing (GDSTR), and node elevation ad hoc routing (NEAR), among others.

Face routing

Face routing represents the inaugural geographical routing algorithm that ensures message delivery. This algorithm operates on the principles of planar graph traversal, utilizing structures such as the Gabriel graph or the relative neighborhood graph. The traversal occurs along the boundary of the face, adhering to either the left-hand or right-hand rule. Upon completing the traversal of the entire face, the algorithm identifies the nearest node to the intended destination and subsequently navigates through the next face that is closer to that destination. This iterative process continues until the destination is reached. A general structure of face routing is illustrated in Figure 2. Face routing consistently guarantees delivery, provided that at least one viable path exists. Numerous variants of face routing have been developed to enhance efficiency, including path-vector face routing (PFR), adaptive face routing (AFR), bounded face routing (BFR), other adaptive face routing (OAFR), and other bounded face routing (OBFR), among others. However, due to their reliance on planar graph traversal, face routing algorithms are not applicable to three-dimensional networks.

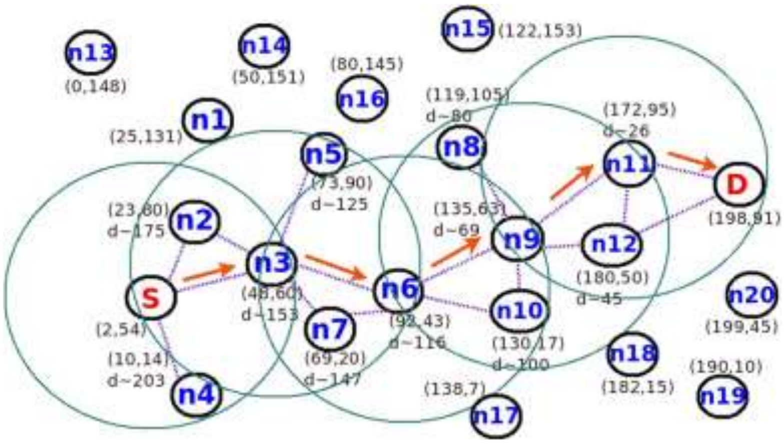

Figure (1) Greedy forwarding

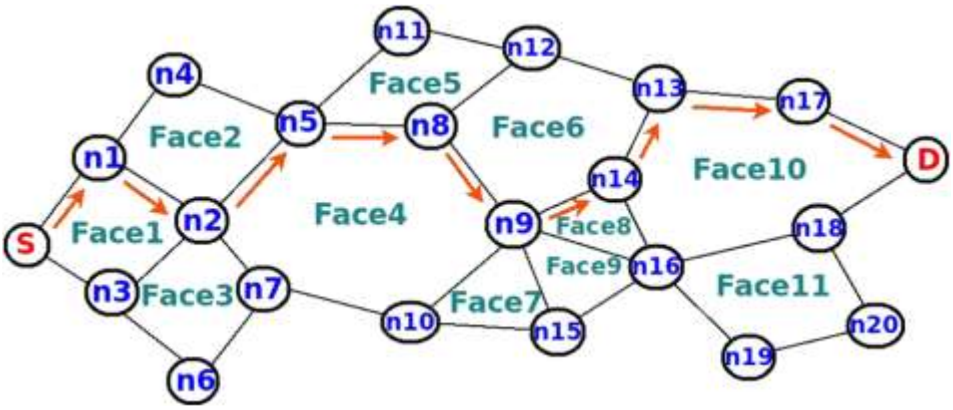

Figure (2) Face routing

3D geographical routing

A significant number of researchers have concentrated their efforts on two-dimensional networks, developing solutions that utilize face routing and greedy forwarding methods. Face routing is dependent on planar graphs, which cannot be applied in three-dimensional spaces, while greedy forwarding techniques encounter challenges related to local minima. Consequently, there is a pressing requirement for routing techniques that are specifically designed for three-dimensional geographical contexts. Protocols such as GPS, 3D location services [16, 17], and algorithms for 3D virtual coordinates [12, 18, 19] can facilitate the acquisition of three-dimensional coordinates for nodes, thereby simplifying the handling of routing issues in three dimensions. This section will explore the categorization of 3D geographical routing techniques, along with the associated research issues and challenges.

Categorization of three-dimensional geographical routing methods based on various criteria

Deterministic routing refers to a method where the routing path is established through a defined deterministic process, devoid of any random elements. Durocher et al. [20] demonstrated through their simulation findings that deterministic routing algorithms fail to ensure the successful delivery of packets in three-dimensional networks. Additionally, Flury et al. [21] examined the energy efficiency of deterministic localized routing algorithms, concluding that they are not effective in 3D networks. In contrast, Xia et al. [22] asserted that they have developed the first deterministic routing algorithm capable of guaranteeing delivery in 3D wireless networks. Conversely, randomized routing schemes involve the random selection of paths. In these algorithms, the current node randomly chooses a neighboring node to advance towards the destination. Numerous researchers [25, 26, 21, 27] have proposed randomized routing protocols specifically designed for 3D wireless networks. In the context of greedy versus recovery routing, a node in greedy mode consistently identifies the nearest neighbor to the destination. Pure greedy routing algorithms are only effective in ideal conditions where local minimum issues do not arise. Most 3D geographical routing strategies initiate in greedy mode and transition to recovery (bypass) mode when a local minimum is encountered [11, 28–32].

The distinction between virtual coordinates and physical coordinates is crucial in geographical routing protocols, which depend on node location data. The initial step involves acquiring either physical or virtual coordinates. Physical coordinates can be determined through location services such as GPS or by employing localization algorithms. However, in extensive sensor networks comprising thousands of nodes, manually assigning coordinates is impractical, and equipping each node with GPS technology is prohibitively expensive. Consequently, utilizing 3D virtual coordinates emerges as a viable alternative. Several researchers have introduced effective techniques for generating virtual coordinates. The comparison between virtual coordinates and physical coordinates is essential for geographical routing protocols, which rely on the location information of nodes. The primary requirement is to acquire either physical or virtual coordinates. Physical coordinates can be obtained through location services like GPS or by utilizing localization algorithms. However, in large sensor networks with thousands of nodes, manual assignment of coordinates is impractical, and providing GPS for each node incurs significant costs. Therefore, employing 3D virtual coordinates presents a feasible solution. Numerous researchers have suggested efficient methods for generating virtual coordinates. Physical coordinates are generally expressed in a fixed format, such as the X, Y, and Z axes or in terms of longitude, latitude, and altitude. Conversely, virtual coordinates do not adhere to a specific format, with researchers employing various representations in their proposed protocols. The format of virtual coordinates may or may not correspond to that of physical coordinates.

Literature survey

In study [11], the authors presented a novel algorithm for three-dimensional wireless networks that integrates a spanning tree with a two-dimensional convex hull, referred to as greedy distributed spanning tree routing (GDSTR-3D). This algorithm allows each node to retain information regarding its two-hop neighbors. The GDSTR-3D algorithm initiates packet forwarding using a greedy method, attempting to locate a one-hop neighbor that is closer to the destination than the current node. If this approach is unsuccessful, it then seeks a two-hop neighbor that is nearer to the destination. If both attempts fail, the packet is routed along the edges of the spanning tree. Each node within the spanning tree compiles the location data of its subtree through the use of two-dimensional convex hulls. Rubeaai et al. [33] have proposed a novel 3D real-time geographical routing protocol (3DRTGP) for time sensitive applications in wireless networks. They have introduced an adaptive packet forwarding region (PFR) so that a transmitted packet can be received in PFR only. The purpose of PFR is to restrict the duplicate packet transmissions, avoid congestion and collisions. The forwarding decision depends on the number of nodes in PFR and the queuing delay in forwarding nodes. Initial PFR value is determined based on network density, but if the packet is not received by any node in given PFR, then it increases the PFR twice every time until finding a forwarding node or covers the maximum possible coverage area. If no such node is found, it will send the packet back to the previous node for an alternative path. Moreover, each node maintains three types of lists named Broadcast List, Retransmit List, and Void Node Packet List to track the packet so that nodes can take routing decision. Broadcast List stores the packet id of each forwarded packet to check whether the received packet is already transmitted or not. Retransmit List keeps the packet id of recently transmitted packets which may require during retransmitting the packet in the case of void node problem (VNP). Void Node Packet List tracks the packets received from the same sender multiple times, which shows VNP and adjust the PFR.

Xia et al. [34] introduced a distributed and deterministic algorithm known as trace-routing for Wireless Sensor Networks (WSNs). The primary aim of trace routing is to navigate away from local minima while maintaining consistent storage, communication, and computational overhead. Initially, the trace-routing employs a greedy strategy until the packet encounters a local minimum. At this point, it establishes a virtual cutting plane that connects the destination and the local minimum, allowing for the intersection of the boundary surface to preserve a trace. The packet then progresses along with this trace to escape the local minimum. The authors conducted experiments using Crossbow sensors and implemented the trace-routing algorithm on a comprehensive simulator to assess routing efficiency. The trace-routing method ensures guaranteed delivery within strongly connected networks. Additionally, the authors validated the correctness of their proposed algorithm in both continuous and discrete environments. They compared their findings with GDSTR-3D [11] and HWE [35], demonstrating that trace routing offers superior routing stretch and greater stability against localization errors. However, the authors assert that their algorithm does not depend on any specific communication model (such as UBG or quasi-UBG), although they did take into account the maximum transmission range, which aligns with communication models, leading to some ambiguity. Furthermore, the method for tracking the coordinates of mobile sensor nodes remains unclear. The algorithm relies on the boundaries of holes to recover from local minima, resulting in an overload of boundary nodes. Consequently, the proposed algorithm lacks load balancing and energy efficiency.

Wang et al. conducted simulations of the SLICE [36], SINUS [37], high genus [38], and random-walk [21] algorithms to evaluate their performance. Their findings indicated that SLICE exhibited the least distance distortion and demonstrated superior performance in terms of routing stretch and load balancing compared to the other algorithms tested. Furthermore, they confirmed that SLICE ensures the reliable delivery of messages between any two nodes. The study also highlighted SLICE's capability to effectively manage gaps within the network. It necessitates a lower storage cost per node, as it does not require the retention of neighboring nodes' locations, thereby enhancing its overall applicability and resilience. SLICE operates under the assumption that nodes are evenly distributed across the designated area. While it presents less distortion than SINUS, it is not entirely free from distortion. Additionally, it incurs additional message costs due to retransmissions in the event of unreliable communication links. The algorithm is based on a triangulated structure within a 3D network, which may lead to performance compromises in smaller networks or those with non-uniform density.

A review of various 3D geographical routing protocols has been conducted, with a comparative analysis presented in Tables 3 and 4. It has been observed that a significant number of researchers have focused on routing stretch and the management of local minima. When efforts are made to address the local minimum issue, boundary nodes often become overloaded. Consequently, achieving a balance between local minimum management and load balancing presents a considerable challenge. Improper load balancing can lead to a reduction in network lifespan. To mitigate these challenges, factors such as storage complexity and control message complexity may increase, potentially resulting in higher costs. Additionally, the transmission of periodic messages can adversely affect network longevity. Although these challenges have been identified and addressed in 2D networks, they remain significant obstacles for 3D networks due to their intricate structure. Beyond these well-established challenges, predicting mobility within a mobile network poses its own difficulties. In mobile networks, coordinates change rapidly, making coordinate prediction a complex task.

Conclusion

The aim of this paper was to identify the research issues and challenges associated with 3D geographical routing. The primary difficulties encountered with these algorithms include achieving a balance among stretch, mobility, storage complexity, and void management. Our analysis indicates that researchers have explored both simple 3D structures and high-genus 3D structures. The high-genus structure is particularly suitable for real-world applications such as tunnels, building corridors, caves, and mines. However, its functionality relies on supplementary geometrical algorithms, including Reeb graphs, Ricci flow, Mobius transformations, Morse theory, and geodesic patterns. Furthermore, there has been limited research on mobile 3D geographical routing, such as in the contexts of UAVs and FANETs, indicating that geographical routing in the presence of mobility remains a promising area for further investigation.

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