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3D geographical routing protocols in wireless ad hoc and sensor networks: an overview

Srimanta Mohapatra, Rojalin Nayak, Sushree Madhusmita Behera, Anita Subudhi
Department of Computer science and Engineering, NM Institute of Engineering and Technology,Bhubaneswar , Odisha
Department of Computer science and Engineering, Raajdhani Engineering College,Bhubaneswar,Odisha
Department of Computer science and Engineering ,Aryan Institute of Engineering and Technology, Bhubnaeswar , Odisha
Department of Computer science and Engineering,Capital Engineering College, Bhubnaeswar , Odisha

ABSTRACT: *Geographical routing is a prominent area of research in wireless networks where route establishment is based on known locations of wireless nodes. The location may be an exact physical location or virtual location. Many geographical routing protocols based on greedy and face routing approach have been designed for 2D networks, but these protocols may not be suitable in 3D environment like hill area, airborne networks, underground networks, underwater networks and so forth. The objective of this paper is to provide the research issues and challenges of geographical routing in the three-dimensional surface. These routing techniques suffer from many problems like energy efficiency, localization, mobility, load balancing, routing stretch, void node problems, etc. These issues have been addressed in the literature survey. In this paper, the recent research papers related to geographical routing have been discussed, but the main focus is on 3D geographic routing techniques, issues and challenges.*

Keywords *3D geographical routing · Localization · Routing stretch · Virtual coordinates · High-genus structure Sensor networks*

I. INTRODUCTION

Wireless ad hoc network consists of stationary or mobile nodes that communicate via the wireless medium such as Bluetooth, Wi-Fi, ZigBee, UWB, etc., where nodes are self-organizing and multi-hop in nature [1]. A wide range of applications of wireless networks like military applica- tions, medical applications, environment monitoring, entertainment, smart cities, smart homes, smart agriculture, smart grid, etc., makes them very popular. Based on the type of geographical structure, wireless networks can be divided into the following four categories:

- Terrestrial wireless networks
- Airborne networks
- Underwater wireless networks
- Underground wireless networks

Terrestrial wireless networks
In this type of networks, wireless nodes are limited to
_territory, and common networks are mobile ad hoc net-works (MANETs), vehicular ad hoc networks (VANETs), wireless mesh networks (WMNs) and wireless sensor net- works (WSNs).
MANETs are the type of networks where nodes are assumed to be mobile. Therefore, communication links with other nodes change frequently. Such networks can be established as per requirement in a small range for a short duration of time, i.e., time of emergency, disaster recovery, relief operations, military applications, etc. [2, 3]. The VANETs use the principles of MANETs but dedicated to vehicle as node where vehicles communicate with the help
of infrastructure provided in term of roadside units. Fur- ther, VANET has predictable node movement patterns, e.g. along the road and vehicles has relatively higher mobility that in case of MANET. Next, we are going to briefly describe the WMN followed by WSN which are commonly used in terrestrial networks.

WMNs are the combination of ad hoc and infrastructure networks [4] which consist of mesh routers, mesh clients and gateways [5]. WMNs can be useful in battlefield surveillance, oil rigs, tunnels, real-time racing-car teleme- try, building automation, etc. Another such type of network is WSN. WSNs consist of numerous sensor nodes to monitor physical or environmental conditions, such as pressure, temperature, humidity, moisture, noise level, mechanical stress level, etc. These nodes have the capa- bility to sense, process and collect information from the atmosphere and send this information to the end user [6]. The sensor networks may or may not be ad hoc in nature; it depends on the application. The applications of WSN include habitat monitoring, agricultural monitoring, health monitoring, forest fire detection, flood detection, etc.

Airborne networks

Airborne network is a type of wireless ad hoc network where communicating nodes are deployed with the aerial vehicles [7]. Usually, nodes fly in the air, so it is called as flying ad hoc network (FANET). The nodes provide air-to- air, air-to-surface and surface-to-air communications [8]. Basically, FANETs are similar to MANETs and VANETs, but FANETs have very high mobility. Unlike VANET, FANET requires the 3D path to fly, so corresponding 3D routing techniques also required [9]. FANETs can be divided into three categories:

1. Manned aircrafts
2. Unmanned aerial vehicles (UAVs) e.g. drones
3. Hybrid (combination of both)

The FANETs are intended to use in aerial communications, navigation and surveillance. At the time of war, the air- borne networks are used to monitor the battlefield and allow military planes to operate without the need of ter- restrial communication infrastructure. Such networks also allow civilian planes to monitor each other's position and flight path.

Underwater wireless networks

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. In the underwater environment, communication is possible through acoustic waves, radio waves or optical waves, but radio waves and optical waves are not efficient, so acoustic communication is preferred [10]. Such a network is also called as an underwater wireless network or underwater acoustic net- work (UAN) [11]. UAN with sensor nodes is termed as underwater wireless sensor network (UWSN). UWSNs are three-dimensional in nature. Based on application and/or deployment technique, UWSNs use different type of underwater vehicles.

- Manned underwater vehicles (MUVs) [12] MUVs are operated by a human pilot. Based on size and resource availability, MUVs can be divided into two categories:
- Manned submersible vehicle A submersible often has very dexterous mobility, provided by propeller screws or pump-jets. Submersibles typically are smaller in size and have a shorter communication range [13]. So, submersible cannot dive into much depth of the ocean.
- Manned submarine vehicle The usage of submarines has been quite prominent, especially during war times when they are used as stealth weapons to destroy opponents' naval vessels. These are rela- tively large in size, hold more resources and a having longer communication range. Hence, sub- marines can work inside the greater depth.
- Unmanned underwater vehicle [14] The vehicle with- out a human pilot, also known as underwater drones. These vehicles may be divided into two categories:
- Autonomous underwater vehicles Operated without direct human input.
- Remotely operative underwater vehicles Controlled by a remote human operator.

Underground wireless networks

The underground wireless networks consist of wireless nodes that operate below the ground surface. Such net- works 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. The nodes may either deployed com- pletely under the soil or open underground space such as underground tunnels and mines [15]. The underground network with sensing capability is known as wireless underground sensor networks (WUSN). Usually, nodes take place at a variety of depths, so these networks are 3D in nature. WUSNs have a variety of applications like, monitoring of soil condition (water concentration, miner- als, toxic substances), monitor the air quality in coal mines,disaster prediction (glacier movement, volcanic eruptions, earthquake, etc.), localization of people in disaster events, monitoring the structural health of buildings and bridges, detection of illegal border crossing, etc. [16].

Based on the locations of the sender and receiver nodes, three different communication links exist in WUSNs, these are underground-to-underground, underground-to-above- ground and aboveground-to-underground [17]. In the next subsection, we have discussed issues and challenges.

Overview of issues and challenges

We have discussed the various types of wireless ad hoc and sensor networks where autonomous nodes communicate with each other in the wireless medium. These networks should provide efficient, low-cost, survivable processing and communication.

Although above discussed wireless networks are dif- ferent from each other based on their applications and working environments, these are similar to each other in many aspects. First, usually these networks are multi-hop in nature, so nodes may not be directly connected to the destination or sink node. Hence, there is a requirement of suitable routing scheme to transfer the data. Second, net- works like, MANET, VANET, FANET, mobile sensor networks and underwater networks have mobility property. Third, some of these networks like underground networks, underwater networks, hill area networks, high building networks, flying ad hoc networks, etc., are 3D in nature. Fourth, wireless nodes are battery powered. Fifth, the nodes are vulnerable to security threats. Hence, we should look over these issues before designing any protocol.

Generally, wireless nodes in such networks are multi- hop in nature, thus message passes through a series of intermediate nodes. Hence, a suitable routing protocol is required to transfer the data. Traditional wireless ad hoc routing protocols are broadly divided into two types: proactive and reactive. Proactive routing protocols are table driven protocols where each node maintains an updated routing table. Each node periodically broadcasts routing information to update the neighbors' table. Hence, it suffers from high storage and communication cost. On the other hand, in reactive routing protocols, the sender node has to establish the route before data transmission. Hence, it increases the communication cost and suffers from initial delay (route establishment delay). Usually, wireless nodes are battery powered and contain a small amount of memory. Therefore, traditional, proactive and reactive routing protocols are not suitable, so geographical routing is a better option. Geographical routing protocols do not need to maintain the routing table, and these are independent of topology change. In addition, these proto- cols are free from initial routing delay. If the source node knows the location of the destination or sink node, then it can directly forward the data.

In literature, Cadger et al. [4] have described routing issues and challenges in the two-dimensional geographic area. Further, Huang et al. [18] also presented a review on 3D geographical routing in wireless mobile ad hoc and sensor networks. In this paper, we have extended the existing literature review on 3D geographical routing techniques and presented recent literature too. We dis- cussed the strengths and weaknesses of existing 3D geo- graphical routing protocols in terms of routing stretch, local-minimum/dead-end problem, obstacle/void handling, energy consumption, load balance, mobility, virtual coor- dinate system and localization issues.

The remaining part of this paper is organized as follows: Sect. 2 describes the basics of the geographical routing protocol, where we have given a brief description of greedy forwarding and face routing. In Sect. 3, we have described the 3D geographical routing in detail. In Sect. 4, we have described the literature survey, and finally, Sect. 5 con- cludes the overall research paper.

II. GEOGRAPHICAL ROUTING

Geographical routing protocols rely on the node's location (physical or virtual) information. Hence, the first require- ment is to obtain the physical or virtual coordinates. The physical coordinates can be obtained by either using the global positioning system (GPS) or using a location service protocol [19–21]. On the other hand, some researchers have proposed efficient virtual coordinate generation techniques [22–24]. Geographical routing techniques are also known as position based, geometric, geographic, location based or directional routing. The example of geographical routing for MANET is location aided routing (LAR) [25]. These techniques rely on some following assumptions:

- Nodes know their own and one hop neighbors' geographical location
- Nodes know the geographical location/region of destination
- Each packet can hold a small amount O(1) of routing information

Geographical routing protocols are broadly divided into two categories: greedy forwarding and face routing.

Greedy forwarding

In greedy forwarding approach, packets are forwarded to the neighbor located closest to the destination at each hop. Greedy routing algorithms are easy to understand and easy to implement. These algorithms are highly efficient for the route discovery process. A general structure of the greedy forwarding approach is shown in Fig. 1 where S and D are source and destination nodes respectively, and other nodes may be used as intermediate nodes. All nodes have their (x, y) coordinates. The value d is representing the Euclidian distance with destination node D. The sky colored circles are denoting the communication range (assumed 50 units) of its centered node. Here, S has three nodes (n2, n3, n4) in its communication range, but n3 has a minimum distance from D so n3 will be next packet forwarding node. Simi- larly, nodes (n3, n6, n9, n11) will perform the same operation and finally, the packet will reach destination D. Sometimes it may happen that packet reached a node where no suitable forwarding node is available (because of network hole or node failure). Due to such problem, the packet may not reach the destination. This condition is known as local minimum, dead-node or dead-end problem. It means greedy routing does not guarantee the path even if some other routing path is available [26]. Some variants of greedy approach are geographic landmark routing (GLR) [27], greedy distributed spanning tree routing (GDSTR) [28], node elevation ad hoc Mrouting (NEAR) [29], and so forth.

Face routing

The face routing is the first geographical routing algorithm that guarantees delivery of the message [30]. The face routing algorithms are based on planar graph traversal (Gabriel graph [31] or relative neighborhood graph [32]). The algorithm traverse through the boundary of the face using left-hand rule (or right-hand rule). After traversing the whole face, it finds the nearest node to the destination. After that, it proceeds by traversing the next face closer to the destination. This process will continue until reaching the destination. Figure 2 presents a general structure of face routing. Face routing always guarantees delivery, if at least one path is possible. There are many variants of face routing have been proposed to improve the efficiency. Some of them are path-vector face routing (PFR) [33], adaptive face routing (AFR), bounded face routing (BFR) [34], other adaptive face routing (OAFR), other bounded face routing (OBFR), and so forth. The face routing algorithms are based on planar graph traversal hence, these are not suitable for 3D networks [35].

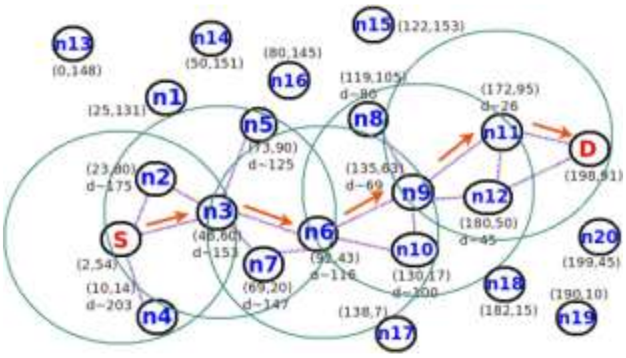

Fig. 1 Greedy forwarding

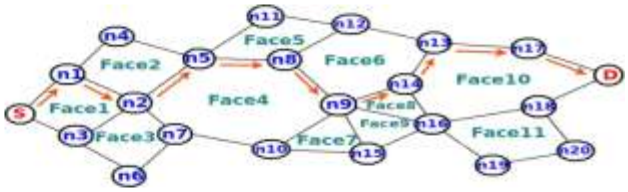

Fig. 2 Face routing

Limitations of 2D algorithms in 3D networks

We have categorized the limitations of 2D algorithms in 3D space following four parts (1) high stretch (2) routing failure (3) ambiguity (4) no guaranteed delivery of message

1. High stretch Sometimes, 2D routing algorithms may take a longer path even if a shorter path is available [21]. It may happen because of lack of knowledge about the third dimension. To understand the concept of the high stretch problem, let's see Fig. 3 where S and D are source and destination nodes respectively. Each node has its 3D coordinates. Assume that the communication range of each node is 50 units. Here, we are using greedy routing approach where a node can forward the packet to its only- neighbor which provides minimum distance from the destination node. We have considered two cases:

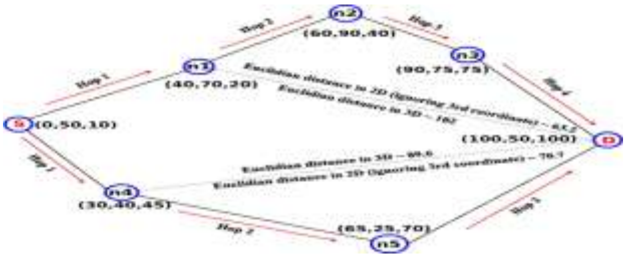

Fig. 3 Routing stretch

Case 1 Ignoring 3rd dimension (2D): node S has two neighbors n1 and n4. Here, we have ignored 3rd coordinate so, distance from the destination node D to n1 and n4 are 63.2 and 70.7 respectively. According to greedy approach, node S will choose node n1 as a next forwarding node. As shown in Fig. 3, it will provide the path S — n1 — n2 — n3 — D with 4 hops.

Case 2 Considering the 3rd dimension (3D): on the other hand, by considering the 3rd dimension, distance from D to n1 and n4 are 102 and 89.6 respectively. Here, the same greedy algorithm will provide the path S — n4 — n5 — D with 3 hops.

As we find that minimum hop distance from S to D is 3, the routing stretch in case 1 is 4=3 ¼ 1:33 whereas, in case 2 it is 3=3 ¼ 1 which is lower than case 1. Hence, a 2D routing algorithm may provide a higher routing stretch than 3D one.

2. Routing failure Suppose we have three nodes A(1, 1, 1), B(8, 8, 5) and C(5, 5, 2) with communication range of each node is 10 units. Node A wants to send a packet to node B. Now, consider 2D greedy routing, so it will ignore 3rd coordinate and assume that nodes are

A(1, 1), B(8, 8) and C(5, 5). The Euclidean distance between node A and node B is p98 (less than 10). Here, 2D algorithm will assume that node B is in communi-cation range of node A but data will not be received are performed badly in 3D networks. The comparative analysis of 3D algorithms with 2D algorithms are shown in Table 1. Thus, we have to focus on 3D geographical routing for 3D wireless networks.

III.3D GEOGRAPHICAL ROUTING

In the literature, there are numerous 2D geographical routing protocols. However, these protocols may not work efficiently if the network is distributed in the 3D space, such as aerial-space, atmosphere, and ocean [21]. Most of the researchers have focused on two-dimensional networks, and their solutions based on face routing and greedy for- warding. The face routing relies on planner graphs which is not possible in 3D space and the greedy forwarding approaches suffer from the local minima problem. Thus, there is a need for 3D geographical routing techniques. The GPS, 3D location service protocols [39, 40] or 3D virtual coordinates algorithms [22, 41, 42] may provide 3D coordinates of the nodes. So, it is easy to work with three- dimensional routing issues. In this section, we are going to discuss the classification of 3D geographical routing tech- niques, research issues and challenges.

Classification of 3D geographical routing
because their actual Euclidean distance is
p
114
(ac-techniques on different basis

cording to 3D coordinates). Hence, node A will under- stand that node B is not available.

If we consider the same case in 3D space, the Euclidean distance between A and B is p114 (greater than 10) so it will use intermediate node C and data will
be delivered successfully.

3. Ambiguity Suppose there are four sensor nodes, A(4, 4, 4), B(6, 6, 4), C(6, 6, 5), D(6, 6, 6). In the case of 2D networks, the third dimension will be ignored. Now, a node with (4, 4) coordinate is the source and a node with (6, 6) coordinate is the destination. Here, routing algorithm will not be able to recognize the exact destination because node B, C and D have the same coordinates i.e. (6, 6). Hence, lack of the 3rd dimension, routing may be ambiguous.
4. No guaranteed delivery of message As we discussed that greedy forwarding does not guarantee the delivery of the message. Face routing works with planner graphs only. The planarity of a graph is not possible 3D geometry. Hence, 2D routing algorithms could not guarantee the delivery of a message in 3D networks.

In the literature, some researchers have developed 3D geographical routing approaches and compared with existing 2D algorithms. They observed that 2D algorithms

- Deterministic versus random Deterministic routing means a routing path can be determined by a proper deterministic process and it does not include any ran- dom search. Durocher et al. [43] proved in their simu- lation results that deterministic routing algorithms cannot guarantee delivery of packets in 3D networks. Moreover, Flury et al. [44] also analyzed that no deterministic localized routing algorithm is energy-ef- ficient on 3D networks. Subsequently, Xia et al. [45] claimed that they provide a first deterministic routing algorithm that provides guaranteed delivery in 3D wireless networks.

On the other hand, a randomized routing scheme comes with the random selection of the path. In such type of algorithms, the current node selects a next neighbor randomly towards the destination node. Many researchers [36, 38, 44, 46] have provided randomized routing protocols for 3D wireless networks.

- Greedy versus recovery In greedy mode, a node always finds a next neighbor nearest to the destination. Pure greedy routing algorithms can be suitable in an ideal environment only where the local minimum problem never occurs. Most of the 3D geographical routing schemes start with greedy mode and switch to recovery (bypass) mode when local minimum occurs [21, 47–50].

Table 1 Comparison of routing algorithms in 3D networks

3D approach	Comparative analysis with 2D algorithms
Randomized_3D [36]	Higher packet delivery rate than compass 2D routing algorithm
GDSTR-3D [21]	Compared with 2D algorithms: S4, BVR, GDSTR, AODV, GPSR, CLPD. These 2D algorithms are performing poorly in terms of message success rate, hop-stretch, message cost and storage cost
OnionMap [24]	Storage cost of OnionMap is 5 times smaller than existing 2D algorithms VBR and S4. Message cost of VBR and S4 is also higher
MDT [37]	MDT is better than GPSR, CLPD in terms of message success rate. MDT has better routing stretch than GPSR, GDSTR and VRR
ABVCap_3D [22]	Lower storage and message cost than 2D algorithms like ABVCap, VCap
ABLAR [38]	The delivery rate is higher than conventional 2D routing algorithms

- Virtual coordinates versus physical coordinates Geographical routing protocols rely on the node location information. Hence, the first requirement is to obtain the physical or virtual coordinates. The physical coordinates can be obtained by either using a location service such as GPS or using a localization algorithm [19–21]. On the other hand, for large sensor networks with thousands of nodes, the manual coordinate assignment is infeasible and providing GPS service with each node is costlier. Hence, a possible solution is to use the 3D virtual coordinates. Some researchers have proposed efficient virtual coordinate generation techniques [22–24, 51]. The physical coordinates have fixed format in the form of X, Y and Z axis or in the form of longitude, latitude and altitude. However, there is no fixed format for virtual coordinates. Researchers have used different formats for virtual coordinates in their proposed protocols. The format of virtual coordinates may or may not be identical to physical coordinates.
- Simple structure versus high-genus structure The genus-n of a graph is simply defined as a minimum number of handles n on the sphere. In other words, genus-n can be defined as a maximum number of times one can cut the surface without disconnecting it. The terms handle, and genus can be used interchangeably. The examples of the genus structure are shown in Fig. 4. The planner graph or rigid sphere has genus-0 structure. The detailed description about genus structure is available in [52–54].

The general 3D routing algorithms are suitable for the simple 3D structure, but these algorithms may not perform well in high-genus structure. The complex 3D surface like underground tunnels, corridors, coal mines, etc., is termed as high-genus structure. The mapping between the geographical region and the genus structure

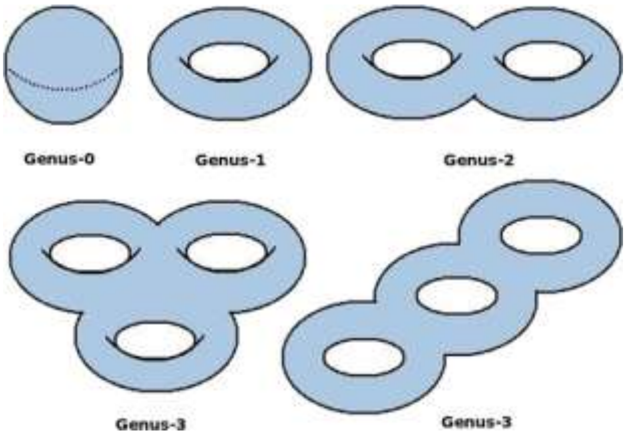

Fig. 4 Sample genus structures

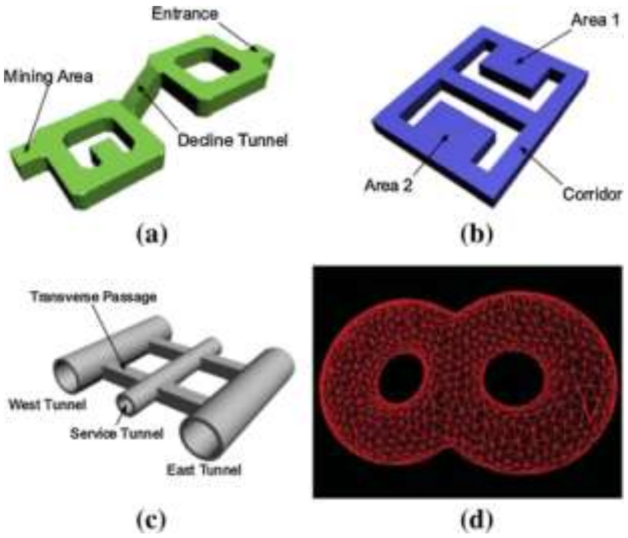

Fig. 5 The networks of a coal mine tunnels; b corridors of buildings; c underground tunnels. These three networks are homotopically equivalent to d a 3D genus-2 network [53]

is presented in Fig. 5. In literature [23, 52, 53], researchers have proposed the high-genus based routing algorithms for complex 3D networks.

- Beacon-based versus beaconless In geographical rout- ing, every node keeps the location information of neighbor nodes. In some protocols, this is done by broadcasting beacon messages to one-hop neighbors periodically. Such protocols use Beacon-Based location exchange mechanism [55]. Whereas, in some other protocols, a node sends some beaconless message periodically to some relevant nodes only [56, 57]. Abdallah et al. [47] proposed the semibeaconless mechanism for location exchanging.

In this section, we have studied different approaches to routing protocols in 3D networks. On the basis of the above discussed approaches, we have described different routing protocols in Table 2.

Research issues and challenges

5. Routing stretch is the ratio of measured path length and shortest path length from source to destination in the given network. In other words, suppose, in a particular network S and D are source and destination nodes respectively, and shortest path length between S and D is spl. Now, suppose we are executing a routing algorithm A and measured path length between S and D using algorithm A is mpl. Then routing stretch of algorithm A will be:

$$RS = \frac{mpl}{spl}$$

Leong et al. [28] used two types of routing stretch (1) hop stretch and (2) path stretch. Hop stretch is the ratio of measured hop distance to the shortest hop distance between source and destination. Path stretch is the ratio of the measured Euclidean distance to the shortest Euclidean distance between the source and destination nodes. In general, authors have considered hop stretch only. For a good routing scheme, the routing stretch should be near to 1.

6. Local minimum is a problem of greedy approach where a node doesn't have any next neighbor nearer to the destination. In this case, the greedy approach cannot guarantee the delivery of the message even if another alternate path is available [26, 68]. This problem usually occurs in sparse network's holes. The hole is a part of the network where nodes are either unavailable or unable to communicate. The local minimum problem is also known as dead-end problem or void node problem.
7. Localization is an ability to find the position information of the node [69]. Finding the accurate location of wireless devices is a crucial requirement for location-aware protocols. Hence, it is an essential requirement for geographical routing protocols. One alternative is to use GPS but it is costlier and inefficient. Many researchers have proposed different localization techniques for 2D and 3D networks. Moreover, the localization problem becomes more challenging in a mobile environment.
8. Mobility states the movement prediction of mobile nodes in the network [70]. Many researchers have proposed different mobility models to predict mobility, but predicting accurate mobility is an NP-hard problem. Mobility prediction is relatively easy in VANET because of using a fixed pattern of movement. It becomes difficult in case of the MANET. Moreover, it is the most challenging task for aerial networks.

9. Energy efficiency The nodes in wireless networks are usually battery powered and contain limited power source. In some networks, node recharging might not be possible or it is not cost effective. Hence, designing the energy efficient routing algorithm is an important research issue [71–73]. Abdallah et al. [47] proposed energy-efficient routing algorithms for 3D networks.
10. Load balancing is a part of energy efficiency. It ensures that each node of the network should have an equivalent load so that it can improve the lifetime of the network. Hence, all nodes should die at about the same time. The network lifetime is the time period until the first/last node dies or until a certain percentage of nodes die [74].
11. Security In wireless ad hoc networks, each node acts as a potential router, therefore, each node is vulnerable to security attacks through routing protocols. Usual routing attacks are black hole attacks, wormhole attacks, sink- hole attacks, false routing information attacks, selective forwarding attacks, hello flood attacks, and so forth. These attacks greatly threaten network security and have become a big challenge to geographic routing design [18]. An alternative solution of such attacks is trust management where data should be routed through trusted nodes only [75]. As per best of our literature review, we didn't find any research article related to security in 3D geographical routing. Hence, it can be assumed that either 2D geographical routing techniques (as discussed in [4]) are sufficient to handle security issues in 3D geometry or it is an open area of research.

IV. LITERATURE SURVEY

In [21], the authors have provided a spanning tree and 2D convex hull based algorithm for 3D wireless networks, i.e. greedy distributed spanning tree routing (GDSTR-3D). In

Table 2 Classification of 3D geographical routing algorithms

Technique	Energy aware	Coordinate update policy	Recovery policy	Coordinate type	Network area	Remarks
GRG [44]	Yes	Beacon based	Random	Physical	Simple 3D	Localized memoryless Simple greedy approach Random walk to recover from local minimum
AB3D [36]	No	Beacon based	Random	Physical	Simple 3D	Starts with AB3D and switch to CFace when local minimum occurs
3D ERGrd [58]	Yes	Beaconless	Deterministic	Physical	Simple 3D	Greedy routing for large-scale networks Picking the node with best energy mileage
3DRanDom [46]	No	Beaconless	Random	Physical	Simple	Random route to deal with local minimum problems

GDSTR-3D [21] No Beacon
based
ABVCap_3D [22] Yes Beacon
based
SLICE [23] No Beacon based

OnionMap [24] No Beacon
based
3D

Deterministic Physical Simple
3D
Deterministic Virtual Simple
3D

Deterministic Virtual High genus

Deterministic Virtual Simple
3D
Routing over backbone network to minimize loops in the random phases
Spanning tree and 2D convex hull based algorithm Each node keeps a two-hop neighbor information Axis-based virtual coordinate assignment

Embed the network to a genus-0 open surface and convert it into a planner convex polygon
Assign the virtual coordinates and apply greedy routing Layer decomposition
Virtual coordinates assignment Layer embedding

BLR [57] Yes Beaconless Deterministic Physical Undefined Choose next forwarding node in distributed way
Dynamic propagation delay at each receiving node
MDT [37] No Beacon based
Deterministic Physical Simple
3D
Multihop Delaunay triangulation routing scheme using the greedy approach for d-dimensional (where d ≤
2) networks

Bubble [55]	Yes	Beacon	Deterministic	Virtual	Simple	Combination of greedy and Table-driven routing
		based			3D	Network is decomposed into HSCs
High-genus [52]	No	NA	Deterministic	Virtual	High	Protocol for complex 3D networks

genus
Find the sequence of pants and then apply greedy routing

SINUS [53]	No	Beacon based	Deterministic	Virtual	High genus	Divide high-genus surface to single connected planar surface Apply greedy routing approach
GHG [59]	No	NA	Deterministic	Physical	Simple	Similar to face routing
					3D	Divide the network in PUDTs
3DRTGP [60]	Yes	Beaconless	Random	Physical	Simple 3D	Limits the number of forwarding nodes by restricting forwarding region Nearly meets real-time requirements
Trace [61]	No	Beaconless	Deterministic	Both possible	Simple 3D	Escape from local minimum with constant storage, communication, and computation overhead
PSVC [62]	No	Beacon	Deterministic	Virtual	Simple	PSO for virtual coordinate assignment
		based			3D	Greedy approach for routing
GGNG [63]	No	Beacon	Deterministic	Virtual	Simple	Identify all holes in the dual graph

based

EDGR [64] Yes Beacon based
3D

Deterministic Physical Simple
3D

Construct a guide to the navigation on the surface of a hole
Greedy forwarding, dual greedy forwarding and dual perimeter forwarding
Dual path routing to bypass holes Maintains anchor list
Projects 3D plane to 2D in case of routing hole

Table 2 (continued)

Technique	Energy aware	Coordinate update policy	Recovery policy	Coordinate type	Network area	Remarks
3DEHR [65]	Yes	Beacon based	Deterministic	Physical	Simple 3D	Energy harvesting aware approach for nanosatellite networks Specialized for space wireless networks
b-BGR [66]	No	Beaconless	Deterministic	Virtual	Simple	Learning automata based routing approach
					3D	Feedback based learning mechanism
SPF [67]	No	Beacon	Deterministic	Physical	Simple	Flooding based greedy approach

based
3D 3D gabrial graph and 3D relative neighbor graph as graph extraction algorithms

this algorithm, every node keeps two-hop neighbor infor- mation. GDSTR-3D starts with the greedy approach to forward the packet as long as it can find a one-hop neighbor closer to the destination than the current node. If it fails, it searches for two-hop neighbor closer to the destination than the current node. If two-hop neighbor also fails, then GDSTR-3D forwards the packet along the edges of the spanning tree. Each node of spanning tree aggregates the location of its subtree using 2D convex hulls.

In general, using two-hop neighbor information signifi- cantly improves the success rate of the greedy forwarding approach in 3D networks. They have performed real experiments on wireless sensors testbed and simulation experiments on TOSSIM (a simulator for tiny OS) and compared their results with GPSR [76], CLDP [77], GDSTR [28], AODV [78], VRR [79] and S4 [80]. The results concluded that GDSTR-3D is highly scalable than others and routing stretch is very close to 1. Moreover, when the number of entries in the convex hull increases, then storage overhead per node of the respective hull also increases, and some nodes (e.g. root) are very heavily loaded. The time complexity and communication cost of GDSTR-3D are dominated by the computation of 2D convex hulls, i.e., O(nlogn). This algorithm is not suitable for dynamic networks.

In [55] Xia et al. have proposed bubble routing for three- dimensional networks based on greedy approach. It is the combination of both, greedy and table driven routing. The network is decomposed into a set of Hollow Spherical Cells (HSCs) where the number of HSCs depends on the number of inner holes in the network i.e. one HSC for each interior hole. The boundary of HSC is termed as the hollow spherical bubble (HSB). To create HSCs and respective HSBs, outer and inner boundaries must be identified. Authors have used unit ball fitting (UBF) algorithm [81] to determine the boundary nodes. However, it uses virtual coordinates rather than GPS provided actual coordinates.

Based on the position of the source and destination nodes, the routing algorithm is divided into two parts, intra- HSC, and inter-HSC. If source and destination are avail- able in the same HSC then continuous and one-to-one mapping performs between HSB and virtual sphere to enable the greedy routing. If source and destination are in different HSCs, then the routing decision depends on the global routing table. They performed simulation in VC?? and compared results with Spherical-Walk (SW) [44] and boundary routing (BR) algorithms. In the BR routing scheme, packets are routed around the boundary of the void area. In simulation results, bubble routing got 100% data delivery. Moreover, the bubble routing is outperforming with SW and BR in routing stretch and load balance.

The algorithm got guaranteed delivery, better load bal- ance and better stretch with the assumption that no node failure for a given network. However, in practice, wireless nodes may fail during functioning. Moreover, every node has to maintain two routing tables, i.e. local and global. Local routing table stores the neighbor node’s information, hence average table size depends on the density of the network. Global routing table stores the information about other HSCs, hence the table size is directly proportional to the number of holes. In the case of inter-HSC, the packet will first move in the direction of the shared boundary of neighboring HSB. After that, it will move along the boundary that includes the destination node. Thus, bubble routing is not suitable where the number of holes increases. Cai et al. [24] have extended bubble routing [55] and proposed a greedy approach based scalable geometric addressing and routing scheme i.e. OnionMap for 3D sensor networks. They decomposed the 3D network into a set of layers. The layers are connected to each other and forming sphere type structures where hop count defines the layer number. One layer can communicate with its imme- diate upper and down layer only. All layers are concen- trated in the middle of the sphere and maintain onion type structure. Layer construction completes in two phases, layer decomposition, and layer embedding. (1) Layer decomposition: the overall network is decomposed into a set of layers. To decompose the network, the authors have proposed an incremental layer construction method based on common properties. Each layer should have a simple closed surface, and every layer should be connected with adjacent layers so that their mapping to the sphere is pos- sible. (2) Layer embedding: after layer decomposition, coordinates assignment is required, but OnionMap does not depend on actual physical coordinates. Hence, authors have used discrete Ricci flow method [82, 83] and uniformized stereographic projection for assigning the virtual coordi- nates to each node. The layer embedding phase is divided into three parts: triangulation, virtual coordinate genera- tion, and layer alignment. Now, each layer is mapped to a unit sphere so that greedy routing can be performed.

They conducted their simulation under UBG and quasi- UBG [84] radio models. The results concluded that OnionMap could easily handle the void node problem (VNP) with low stretch. Additionally, they have demon- strated that their algorithm is providing high scalability and load balance without boundary detection. The authors have compared their results with Bubble routing [55], BVR [85], GRG [44] and S4 [80] in different hole condi- tions. OnionMap requires less storage than Bubble because OnionMap needs only layering information to maintain the coordinates while Bubble has to store the neighbors' coordinates on same depth. The message transmission cost of OnionMap is O(n), where n is the network size. It takes less routing setup cost than Bubble, BVR and S4. It also indicates that the routing paths of OnionMap are dis- tributed almost uniformly.

OnionMap is yet to be verified on the real testbed. However, the Ricci flow method has been used for virtual coordinates assignment which suffers from texture errors [86]. So OnionMap may suffer from erroneous results. In [86], the authors have used some formula for the additional accuracy of the Ricci flow method. Even, it takes less routing setup cost than other algorithms, but still, it suffers from high initial overhead in layer construction, layer embedding process and virtual coordinate generation process.

Lam et al. [37] proposed multihop Delaunay triangula- tion (MDT) routing scheme using the greedy approach for d-dimensional (where $d \leq 2$) wireless networks. They have used virtual links to handle the local minimum problem and dynamic topology changes (i.e. churn) due to connecting/disconnecting the nodes or physical links. MDT does not use flooding to discover multi hop DT neighbors.

Hence, it is communication efficient. MDT does not use any beacon or landmark node. The authors have compared their results with GRG [44], GPSR [76], CLDP [77], GDSTR [28], GDSTR-3D [21] algorithms and get lowest routing stretch with highest routing success rate. This protocol is simulated in some packet-level discrete-event simulator. They have shown in simulation results that (1) algorithm provides guaranteed delivery of the message for any connected graph, (2) 100% success rate during churn,
(3) routing stretch is close to 1, (4) for an extensive net- work, per node storage, construction and maintenance cost is relatively low and independent of network size.

In the simulation, they have not considered congestion and queuing delay. Hence, the end to end throughput and latency cannot be evaluated. The problem with MDT is that the virtual link may be very long, so maintenance may be costlier. However, the construction and maintenance of MDT are not purely localized and require centralized operations.

Rubeaai et al. [60] 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 trans- mitted 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 BroadcastList, RetransmitList, and VoidNodePacketList to track the packet so that nodes can take routing decision. BroadcastList stores the packet id of each forwarded packet to check whether the received packet is already transmitted or not. RetransmitList keeps the packet id of recently transmitted packets which may require during retransmitting the packet in the case of void node problem (VNP). VoidNodePacketList tracks the packets received from the same sender multiple times, which shows VNP and adjust the PFR.

In 3DRTGP, a node does not need to exchange the beacon messages to monitor the neighbor node.

Additionally, a node does not need to store the location of neighbors. They compared 3DRTGP with ABLAR [38] and some 3D greedy algorithm in OMNET?? (Mixim framework) and shown that 3DRTGP is outperforming in terms of end-to-end delay and miss ratio.

They claimed that 3DRTGP provides real-time requirements for time sensitive applications, but in the case of the void, sender/forwarding node has to wait for timer expiration. So, in the case of multiple void nodes, the time delay will increase. Hence, this claim seems to be questionable for large concave multiple voids. In this algorithm, it is assumed that all nodes are stationary and having a fixed transmission range with radius r. It also suffers from very high storage cost of maintaining the packet_id of each packet at every forwarding node. Moreover, they did not consider mobility and energy awareness issues in this algorithm.

Flury and Wattenhofer [44] proposed a feasible solution for 3D geographical routing. Initially, it starts to greedy approach until caught in a local minimum. After that, it uses random walk (RW) procedure for recovery from the local minimum. Finally, it again continues with the greedy approach. Hence, it is called Greedy–Random–Greedy routing or GRG in short. It uses virtual cubes to track the holes. Moreover, If d is the optimal path length between source and destination, then the worst case complexity of the algorithm is $O(d^3)$.

The authors have provided five different RW techniques to recover from the local minimum. These are RW on the dual, RW on the surface, RW on the graph, bounded DFS on a spanning tree, and bounded flooding. The RW approaches have good performance on dense networks while DFS on the spanning performs well in sparse networks. The algorithms implemented in Sinalgo [89] simulator and shown that RW on the dual has minimum routing overhead.

Even GRG is a feasible algorithm, yet it suffers from following problems: (1) virtual cube approach is costly because it requires 3-hops information. (2) Randomized approach is not practically efficient in every condition. (3) Unit ball graph communication model is used to show the connectivity among wireless nodes, but it is not a practical model.

The Greedy–Hull–Greedy (GHG) routing protocol was proposed by Liu et al. [59], which includes routing on the hull to get rid of the local minimum. GHG is designed for 3D networks, which is similar to face routing of 2D networks. First of all, partition the whole network into a number of closed subspaces using proposed partial unit Delaunay triangulation (PUDT) algorithm whose purpose is to remove the intersecting edges of triangles and provide the recovery from the local minimum. The PUDT may contain additional edges and fewer triangles than UDT.

They have simulated GHG, GRG [44] and DFS [90] on a simulator and verified the efficiency of GHG over DFS and GRG. They believed that every face routing based 2D geographical routing algorithm could be redefined and extended on the PUDT based model. PUDT model includes virtual coordinates, geocast, multicast, uncertain position information handling, and energy efficient routing. Moreover, the PUDT requires only one-hop neighbor information.

The authors have proposed GHG algorithm based on some following assumptions; First, each node knows its location information using GPS receiver; second, all wireless nodes have same communication range; third, it uses unit-ball graph communication model i.e. unrealistic. Deploying GPS with each node increases the deployment cost. Additionally, it suffers from the high cost of creating and maintaining PUDT. GHG does not provide guaranteed delivery and it didn’t consider load-balancing, scalability, mobility issues.

The particle swarm optimization (PSO) [91] based distributed virtual coordinate assignment algorithm named particle swarm virtual coordinates (PSVCs) is presented in [62]. The PSO is a bio-inspired algorithm whose behavior depends on bird flocks and fish schools. The objective of PSVC is to assign the virtual coordinates using PSO algorithm and apply greedy routing. First of all, it chooses a fixed number of reference nodes (four nodes for 2D and six nodes for 3D) at the network boundary. Then assigns the coordinates to each node using the PSO algorithm where primary coordinates allocated to the reference nodes. After that, assign the coordinates to each non-reference node based on hop distance from reference nodes. Finally, PSVC runs the relaxation procedure on coordinates to improve the convexity of virtual topology.

They have simulated PSVC in TOSSIM simulator and compared results with NoGeo [92] algorithm. The simulation results have shown that PSVC is faster and having a lower routing stretch than NoGeo. It also has good scalability on large networks. Moreover, it works better than actual physical coordinates for sparse networks. The authors have successfully tested this algorithm on a real TinyOS (TelosB) mote testbed and proved that PSVC is providing better convexity. Hence, it is a better option in the direction of making geographical point-to-point routing practical for large WSNs.

The PSVC suffers from some limitations also. However, it has a good success rate but it cannot provide guaranteed delivery. It has high routing cost in terms of message cost and link cost. The authors have not considered load balancing and energy efficiency issues.

Xia et al. [61] have proposed a distributed and deterministic dubbed trace-routing algorithm for WSNs. The objective of trace routing is to escape from local minimum with constant storage, communication, and computation overhead. The Trace-routing basically starts with the greedy approach until the packet reaches a local minimum. Then it creates a virtual cutting plane, which holds the destination and local minimum, to intersect the boundary surface to maintain a trace. The packet moves together with the trace to recover from the local minimum.

They experimented with Crossbow sensors and imple- mented trace-routing on an extensive simulator to fig- ure out the routing efficiency. The trace-routing achieves guaranteed delivery with strongly connected networks. Moreover, they proved the correctness of the proposed algorithm with continuous and discrete settings. The authors have compared their results with GDSTR-3D [21] and HWE [45] and proved that trace routing has better routing stretch and more stable against localization errors. The authors have claimed that the proposed algorithm does not rely on any communication model (e.g. UBG or quasi-UBG), but they considered maximum transmission range which is equivalent to communication models. So, it seems confusing. Furthermore, it is still unclear how to track the coordinates of mobile sensor nodes. The proposed algorithm uses the boundary of holes to recover from local minimum. Hence, boundary nodes get overloaded. So, the proposed algorithm is not load-balanced and energy-efficient.

All the above-discussed algorithms are suitable for the simple 3D surface, but these algorithms may not perform well in the complex 3D surface like underground tunnels, corridors, coal mines, etc. Yu et al. [52] have proposed a high-genus algorithm for complex 3D networks. The high- genus structure is already discussed in section III.

In [52], first of all, decompose the network in pants (genus-0 components). After that, search the series of adjacent components and then apply the greedy approach within each component. The authors have claimed that the high-genus algorithm provides guaranteed packet delivery in normal conditions. However, each node has to maintain the routing table for all other components, so per node storage overhead is very high. Furthermore, the other problem with this technique is that, it relies on centralized operation while decomposing the network into genus-0 components. Additionally, this algorithm cannot handle the holes in the network. Thus, this algorithm is impractical for real WSNs.

Yu et al. [53] have proposed a Scalable and dIstributed routing algorithm with guaranteed delivery for WSNs on high geNUs 3D Surface (SINUS) algorithm for complex 3D networks. The SINUS is an extension of the [52] algorithm and it is based on the greedy approach. The key idea is to convert the whole target area into high genus structure and then convert it to the genus-0 surface using cuts. Finally, map this genus-0 surface to planner ring- shaped surface and perform greedy routing.

The authors have used a Geodesic pattern and rotation scheme to construct maximum cut-set of given genus-n surface. The Morse function uses maximum cut-set to slice the network. Then, using Morse theory and Reeb graph, the network is converted into the genus-0 surface with 2n boundaries. These 2n boundaries merged to 2 bound- aries using the Ricci flow method. Hence, it will be flat- tened into a strip. Finally, apply Mobius transform to convert this strip into planner ring-shaped surface then apply greedy routing. Authors have compared their approach with high-genus [52] and Random-walk [44] algorithms and achieved better results regarding routing stretch and load balance.

For routing purpose, each node has to maintain the virtual coordinates only, so no need to store location or angular information. Thus, storage cost is low, hence it is scalable. SINUS do not rely on any radio model, e.g. UDG or quasi-UDG. Additionally, it is fully distributed, so no need to maintain a centralized operation, therefore, no single point of failure. SINUS has O(mn) message com- plexity during the establishment phase where n, m are genus and the number of nodes respectively. SINUS achieves good load balance because it does not always follow boundary nodes.

The drawback with SINUS is that the nodes may not be uniformly distributed. SINUS always converts any shaped surface to ring-shaped surface so, in some cases, it has to travel through a longer path. It also suffers from higher distance distortion. Moreover, it cannot handle the holes/ voids in the network.

In [23] Wang et al. have extended the work proposed in [53] and proposed a new greedy routing scheme for high genus 3D WSNs named scalable and low stretch routIng scheme (SLICE). The basic theme of this paper is to embed the network to a genus-0 open surface which has strictly one boundary and then convert it into a planner convex polygon. Finally, assign the virtual coordinates to this planner convex polygon and apply greedy routing.

First of all, extract the maximum cut set of the genus- n surface area using Morse function and Reeb graph theory. After that, connect these cuts based on depth first search traversal to get a genus-0 open surface with strictly one boundary. Then authors have proposed a variant of the Ricci flow method to flatten the genus-0 open surface into a planner convex polygon. The purpose of this variant is to achieve lower distance distortion resulting lower routing stretch. Finally, assign the virtual coordinates to planner convex polygon and apply greedy routing.

Wang et al. simulated SLICE [23], SINUS [53], high- genus [52] and random-walk [44] algorithms to analyze the results. They found that SLICE has smaller distance distortion and best performance in routing stretch and load balance among all simulated algorithms. They also achieved guaranteed delivery of message between any pair of nodes. Additionally, they showed that SLICE could easily handle the holes in the network. It requires less storage cost per node, i.e. doesn't need to store the neighbor's location. Thus, it improves overall applicability and robustness.

SLICE assumes that nodes are uniformly distributed among the target area. It has lesser distortion than SINUS, but it is not distortion-free. It also suffers from extra message cost due to retransmission, in case of the unreli- able communication link. Moreover, it relies on a trian- gulation form of 3D network. Hence, it has to compromise with performance in case of small size network or non- uniform density of the network.

We have discussed various 3D geographical routing protocols. Their comparative analysis is shown in Table 3 and 4. Here, we have figured out that most of the researchers have worked on routing stretch and local minimum handling. Whenever someone tries to resolve the local minimum problem, then boundary nodes get over- loaded. Hence, a trade off between local minimum han- dling and load balancing is a big challenge. When nodes are not properly load-balanced, then network lifetime get reduced. To resolve these issues, other factors like storage complexity and control message complexity may increase. Such problems may lead to higher cost. Again, periodic messages may affect network lifetime. Although these issues are identified and resolved in 2D networks still these are big challenges for 3D networks because of its complex structure.

Other than these well-defined issues, mobility prediction in a mobile network is also a challenging job. In mobile networks, coordinates are changing rapidly. So, coordinate prediction or coordinate generation in the 3D plane becomes a big problem. Very few researchers have worked on mobile wireless networks with geographical routing.

V. CONCLUSION

The objective of this paper was to capture the research issues and challenges related to 3D geographical routing. The major challenges with these algorithms are to balance among stretch, load balancing, mobility, storage

Table 3 Comparison of 3D geographical routing algorithms

Algorithm	Storage complexity	Message complexity	Routing stretch	Load balance	Scalability	Local minimum	Coordinate type	Network decomposed	Mobility	Ensured delivery
GDSTR-3D [21]	High	Mid	Yes	No	Yes	Yes	Physical	Hull tree	No	Yes
MDT [37]	Low	Low	Yes	No	No	Yes	Physical	Distributed Delaunay triangulation	Yes	Yes
OnionMap [24]	Mid	Mid	Yes	Yes	Yes	Yes	Virtual	Virtual layers	No	Yes
Bubble [55]	Mid	High	Yes	Yes	Yes	Yes	Virtual	HSCs	No	Yes
High-genus [52]	High	High	No	No	Yes	No	Virtual	Pairs of pants	No	No
SINUS [53]	Low	Mid	Yes	Yes	Yes	No	Virtual	Genus	No	Yes
SLICE [23]	Low	Mid	Yes	Yes	Yes	Yes	Virtual	Genus	No	Yes
GHG [59]	Mid	High	Yes	No	No	Yes	Physical	Hulls	No	No
GRG [44]	Low	High	Yes	No	No	Yes	Physical	NA	No	No
3DRTGP [60]	High	Mid	No	No	Yes	Yes	Physical	PFR	No	No
Trace [61]	Mid	Mid	Yes	No	No	Yes	Both	Virtual cutting plane	Yes	No
PSVC	Mid	High	Yes	No	Yes	Yes	Virtual	NA	No	No

[62]										
3DIAIR [87]	Mid	Mid	Yes	No	No	No	Physical	Convex hull	No	Yes
GGNG [63]	Mid	Mid	Yes	No	No	Yes	Physical	NA	Yes	Yes
ABVCap-_3D [22]	Mid	High	Yes	No	No	Yes	Virtual	NA	No	Yes
EDGR [64]	Mid	High	No	Yes	Yes	Yes	Physical	NA	Yes	No
3DEHR [65]	Low	Mid	Yes	Yes	Yes	Yes	Physical	NA	Yes	No
FBMF [88]	High	Mid	No	No	No	No	Physical	NA	Yes	No
b-BGR [66]	Low	High	No	No	No	No	Virtual	NA	No	No
SPF [67]	Low	High	Yes	No	Yes	Yes	Physical	NA	Yes	Yes

Table 4 Assumptions, merits and demerits of 3D geographical routing algorithms

Technique Assumptions Merits Demerits

GDSTR-3D [21] Every node keeps two-hop neighbor information
Channel is collision free Static network topology
MDT [37] No link failure Dynamic network

OnionMap [24] UBG and quasi-UBG radio model
Only connectivity information required

Bubble [55] No node failure
Nodes are uniformly distributed

High-genus [52] Any graph can be embedded on a topological surface
The embedding topological surface has an essentially unique Riemannian metric with constant curvature
SINUS [53] Nodes should be uniformly distributed
Deployment area should be hole-free Only connectivity information is required
SLICE [23] Nodes should be uniformly distributed
Packets are routed between non- neighbor boundary nodes

GHG [59] Each node uses a GPS receiver All nodes having same communication range
Uses unit-ball graph communication model
GRG [44] Each node knows its own, neighbors' and destination's coordinates UBG radio model
3DRTGP [60] Each node knows its own and destination's coordinates
All nodes are stationary having same transmission range
Trace [61] Random waypoint mobility model
The tetrahedron structure and triangular boundary surfaces

PSVC [62] Stationary nodes
Some constant number of nodes available at network boundary
Practical 3D deployment Highly scalable
Routing stretch close to 1

Multidimensional routing ability About guaranteed delivery with

dynamic networks
Per node storage cost is relatively low
Robustness to connection irregularity
Low communication cost Easy to handle the holes
Guaranteed delivery, low stretch, load balanced

Scalable
Suitable for complex structure Guaranteed delivery in normal
conditions

Suitable for tunnels, coal mines, corridors
Load-balanced, Scalable

Smaller distance distortion Better load balance
Easy to handle the holes

Less overhead, uncertain position information handling
Energy-efficient
Handles local minimum problem

Memoryless, localized Relatively easy
Applicable for real networks No need to keep neighbor's
coordinates
No periodic beacon message required
Constant storage, communication and computation overhead
Deterministic in nature Works better than physical
coordinates on sparse networks
No assumptions on network topology
Increase storage overhead
Not suitable for dynamic networks

Construction and maintenance of MDT are not purely localized and require centralized operations

Suffers from texture errors High initial overhead

High storage complexity
Badly affect performance when the number of holes increases
High storage overhead
Centralized operation during decomposition of the network
Cannot handle the holes
No void handling
Suffers from higher distance distortion
Not suitable for randomly distributed nodes
Not distortion free High message cost
Affects performance in case of nonuniform node density
High deployment cost
High cost of creating and maintaining PUDT Didn't consider load-balancing, scalability,
mobility issues

High cost of creating and maintaining PUDT UBG is not a practical model
GPS with each node increases deployment cost No mobility support
It cannot provide real-time data delivery in case of multiple timeouts or concave voids

Boundary nodes get overloaded
No load-balancing, no energy-efficiency

Cannot provide guaranteed delivery High message and link maintenance cost

Table 4 (continued)

Technique Assumptions Merits Demerits
GGNG [63] Each node has unique-Id, same
transmission range and contains 3-hop neighbor information
Unit ball graph communication model ABVCap_3D [22] Each node have unique-Id and same
transmission range
Unit ball graph communication model
EDGR [64] Nodes are distributed according to
Poisson distribution
Node knows location and residual energy of neighbors
Location of node act as node Id 3DEHR [65] Network of nanosatellite nodes
Artificial potential field is applied to find next forwarding node

SPF [67] Unit ball graph communication model 3DGG and 3DRNG used for subgraph
extraction
Compatible with mobile sensors Guide to the navigate the hole's
surface

Easy to void handling
Storage complexity independent to obstacles
Load balanced and energy aware Provide more than one path Provide optimal route in case of
routing hole
Energy harvesting (EH) aware Load balanced, better hop
stretch, packet delivery
reliability, solves routing hole problem
Lower routing overhead than flooding
Higher packet delivery rate Loop free routing
Not guarantee delivery in mobile networks Strictly work with unit ball graph radio model
only High storage cost

Hign message complexity Cannot handle network dynamics No mobility support
May increase delay when dealing with routing hole
Projecting 3D network to 2D network may lead to routing failure

Routing is based on EH and EH depends on solar panel, so lack of solar energy or solar panel failure may lead to routing failure

Not energy efficient Flooding based algorithm

complexity, computational complexity, scalability, guaranteed delivery and void handling. We have analyzed that researchers have worked on the simple 3D structure and high-genus 3D structure. The high-genus structure is appropriate for practical scenarios like tunnels, building corridors, caves, mines, etc. However, its working depends on additional geometrical algorithms like Reeb graph, Ricci flow, Mobius transform, Morse theory, geodesic pattern, etc. Moreover, very few researchers have focused on mobile 3D geographical routing e.g. UAV, FANET so geographical routing with mobility is a research prone area.

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