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Survey paper

A survey on routing algorithms for wireless Ad-Hoc and mesh networks

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ABSTRACT

Wireless networking technology is evolving as an inexpensive alternative for building federated and community networks (relative to the traditional wired networking approach). Besides its cost-effectiveness, a wireless network brings operational efficiencies, namely mobility and untethered convenience to the end user. A wireless network can operate in both the "Ad-Hoc" mode, where users are self-managed, and the "Infrastructure" mode, where an authority manages the network with some Infrastructure such as fixed wireless routers, base stations, access points, etc. An Ad-Hoc network generally supports multi-hopping, where a data packet may travel over multiple hops to reach its destination. Among the Infrastructure-based networks, a Wireless Mesh Network (with a set of wireless routers located at strategic points to provide overall network connectivity) also provides the flexibility of multi-hopping. Therefore, how to route packets efficiently in wireless networks is a very important problem.

A variety of wireless routing solutions have been proposed in the literature. This paper presents a survey of the routing algorithms proposed for wireless networks. Unlike routing in a wired network, wireless routing introduces new paradigms and challenges such as interference from other transmissions, varying channel characteristics, etc. In a wireless network, routing algorithms are classified into various categories such as Geographical, Geo-casting, Hierarchical, Multi-path, Power-aware, and Hybrid routing algorithms. Due to the large number of surveys that study different routing-algorithm categories, we select a limited but representative number of these surveys to be reviewed in our work. This survey offers a comprehensive review of these categories of routing algorithms.

In the early stages of development of wireless networks, basic routing algorithms, such as Dynamic Source Routing (DSR) and Ad-Hoc On-demand Distance Vector (AODV) routing, were designed to control traffic on the network. However, it was found that applying these basic routing algorithms directly on wireless networks could lead to some issues such as large area of flooding, Greedy Forwarding empty set of neighbors, flat addressing, widely-distributed information, large power consumption, interference, and load-balancing problems. Therefore, a number of routing algorithms have been proposed as extensions to these basic routing algorithms to enhance their performance in wireless networks. Hence, we study the features of routing algorithms, which are compatible with the wireless environment and which can overcome these problems.

1. Introduction

1.1. Wireless network

Among the various access networking technologies, wireless networking has evolved as a cost-effective alternative to the traditional wired access networking approaches,

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e.g., Digital Subscriber Line (DSL) and cable modem (CM). Being an untethered medium, using a wireless network, wiring need not reach all the way to the end users; thus, a wireless network saves on the Infrastructure cost and offers user mobility. A wireless local area network (WLAN) can operate in both the "Ad-Hoc" and the "Infrastructure" modes.

1.2. Wireless Ad-Hoc Network

Fig. 1 shows a wireless Ad-Hoc network, which is a decentralized network where each node (end-user node) is able to forward data packets for other nodes. The main objective of an Ad-Hoc network is to maintain the node's connectivity and reliably transport the data packets. In addition, each node dynamically determines its next hop based on the network topology. One type of Ad-Hoc network is the Mobile Ad-Hoc Network (MANET). MANET is a self-configuring network of mobile nodes (also called routers), which can form a dynamic topology. The routers could move and organize themselves on-the-fly; thus, the topology of the wireless network may change rapidly and unpredictably. Such a network may operate in a standalone fashion, or may be connected to the rest of the Internet.

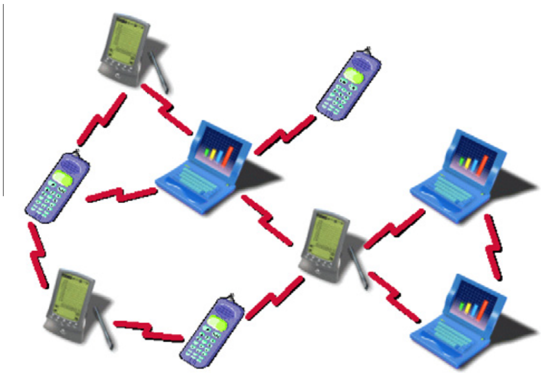

Fig. 1. Ad-Hoc network.

1.3. Wireless Mesh Network (WMN)

Fig. 2 shows an Infrastructure-based wireless network. Unlike the Ad-Hoc network, in an Infrastructure-based network, the end-user connectivity is managed by a special node, known as an access point (AP). Furthermore, an AP can coordinate between another AP and an end user. Among Infrastructure-based networks, Wireless Mesh Network (WMN) has gained considerable popularity in the past decade, especially due to its multi-hopping[1] capability (similar to MANET). In a WMN, nodes assist one another in transporting a data packet through the wireless media. In principle, these networks can be extended to larger networks with greater number of nodes, and can still maintain the required end-to-end connectivity. The WMN consists of a number of Mesh Nodes (MN). There are two types of mesh nodes, namely routers and access points (APs). While the routers can perform data packet forwarding, APs are capable of both forwarding and serving the end users. Gateways form a subset of MN, which can connect either to the wired backbone network, or to a neighboring mesh network.

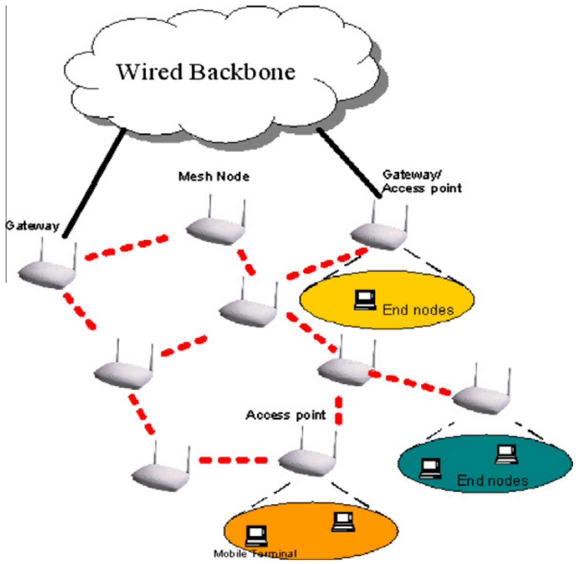

Fig. 2. Wireless Mesh Network (WMN).

1.4. Routing in wireless Ad-Hoc and mesh networks

The connectivity and routing in the Ad-Hoc and the Infrastructure-based networks depend largely on different aspects of the network functionalities. In addition to maintaining connectivity, the end user in the Ad-Hoc network can also perform routing. However, in a WMN, a mesh node is responsible for these functionalities. Hence, the end user in a WMN consumes significantly less energy and can run high-end applications compared to the end users in an Ad-Hoc network.

Routing is a challenging problem in dynamic and mobile wireless networks. A good routing solution should have the characteristics of being decentralized, self-organizable, and self-healing. At the same time, a routing solution should adapt itself to the bandwidth limitation of the wireless spectrum, and exploit the multi-hopping property for better load balancing. Routing also needs to consider power awareness to provide an energy-efficient solution for wireless networks. The above concepts will be elaborated below.

Routing is said to be decentralized when routing decisions are the responsibility of each node (router) separately, according to a certain pre-approved protocol between these nodes. In decentralized routing, there is no specific bottleneck central node at which routing decisions are made. Self-organization is a process of evolution where the development of a new and complex structure takes

[1] The concept of multi-hopping is very generic and applies to both wired network and wireless network (especially WMN).

place primarily in and through the system itself. In a wireless network, if the network organizes itself to improve performance, or readjusts itself in case of a failure, then the network is self-organizing. Self-healing is a recovery process where routing could quickly overcome the negative effects of a failure; thus, self-healing improves the network's fault tolerance.

Bandwidth limitation, which is a result of the limited channel capacity, may occur because of the limited wireless spectrum, its shared medium nature, and due to concurrent transmissions. Being a shared medium, all wireless links have to share some common channels or frequencies.[2] Thus, simultaneous transmissions on a single channel may lead to significant bandwidth reduction. Co-channel transmission, when two nodes use the same channel to transmit their data packets simultaneously, can also cause interference, if the nodes are close to each other, and this is an important issue to be considered when managing and designing the wireless network. This is because the more the interference among nodes, the more data loss occurs which leads to overall network-performance degradation.

Multi-hopping means that one can setup a path over multiple nodes to reach the destination. In other words, the path between the source and the destination nodes goes through multiple intermediate nodes.

Power awareness is crucial in a mobility-based wireless network, particularly in an Ad-Hoc network, where nodes need to reduce their power consumption to increase their battery lifetime if the nodes are not connected to a power outlet. In this case, the transmission power should be carefully chosen since the reduction in the transmission power level may lead to a reduction in the distance that the node can cover or what is called "transmission range". Hence, a node may not be able to directly connect to other distant nodes in the network, which reinforces the principle of multi-hopping in order to carry traffic among various pairs of nodes.

1.5. Dimensions of routing-algorithm categories

The early routing algorithms (RA) for wireless networks are classified, similar to those for wired networks, according to centralized/distributed and proactive[3]/reactive[4] categories. We refer to this type of categorization as the classical dimensions of routing-algorithm categorization. However, in recent years, the wireless routing algorithms in the literature have evolved to encompass the unique challenges posed by wireless networks, which, in turn, introduce several novel routing categories, as shown in Fig. 3. These include Geographical, Multicasting, Geo-casting, Hierarchical, Flow-aware, Power-aware, Multi-path, Hybrid, and Mesh routing algorithms. The companion table (Table 1) expands on the acronyms of the RAs. The new method of categorizing the routing algorithms creates new and significant dimensions of wireless routing-algorithm categories compared to the wired-network routing-algorithm categories or the classical dimensions of routing-algorithm categorization.

Multiple categories of routing algorithms can share some common properties. As a result, several routing algorithms can be placed into multiple categories. For instance, the Zone-based Hierarchical Link State (ZHLS) [62] algorithm is listed under two different categories: Geographical as well as Hybrid. All of these routing algorithms can also be categorized as centalized/distributed and proactive/reactive.

1.6. Wireless routing-algorithm issues

Using basic routing algorithms in a wireless environment could lead to problems such as large area of flooding,[5] empty set of neighbors (when Greedy Forwarding technique is used), flat addressing, widely-distributed information, large power consumption, interference, and load-balancing problems. Therefore, several routing algorithms from different routing-algorithm categories were proposed to solve one or more of these issues.

1.7. Related work

A number of surveys have been conducted on routing algorithms in wireless networks with each focusing on a particular category and/or discussing a set of algorithms in each category. Due to the large number of the surveys that have studied different routing-algorithm categories, we limit our review to some of these surveys. For example, the surveys in [38,45] discuss the scalable and power-efficient issues in the Geographical routing algorithm; [38,45] give some examples of single-path greedy packet forwarding, power-aware routing, and planar graph routing as a recovery strategy. The authors of both [1,79] study the efficiency of different Geographical routing algorithms in a 3-D Ad-Hoc network. Similarly, the study in [52] surveys the Geographical routing algorithms, and compares them with the flat routing (proactive/reactive) and Hierarchical routing algorithms; [52] presents a few routing algorithms, which are included in each of these categories. Additionally, [106] studies a set of Geographical routing algorithms. On the other hand, the work in [112] focuses on the Multi-path routing algorithms. Refs. [2,3] are extensive surveys that explore the WMN in detail. Refs. [2,3] include examples of Geographical, Hierarchical, and Multi-path routing algorithm categories. Finally, in addition to the categories discussed in [2], Ref. [80] also discusses Multi-cast routing. However, our paper encompasses a comprehensive survey of all the above routing-algorithm categories.

[2] The concept of multiple channels (multi-channels) is included in this discussion because the notion of multi-channels with the existing bandwidth limitation means that the multi-channel system can be divided into single-channel subsystems where each channel is represented by the subset of links that are sharing this particular channel.

[3] Proactive is also called table-driven routing.

[4] Reactive is also called on-demand routing. Ref. [51] studies the performance of both proactive and reactive routing approaches in wireless networks.

[5] Flooding is a packet-forwarding process where each node broadcasts a packet to every attached neighbor excluding the source neighbor from which the packet arrived. Flooding is a quick process that is used in a large network to exchange routing information updates. Generally, the flooding area is the area of the entire network where the flooding process is taking place. However, this area can be reduced by preventing a subset of the network nodes from participating in the forwarding process.

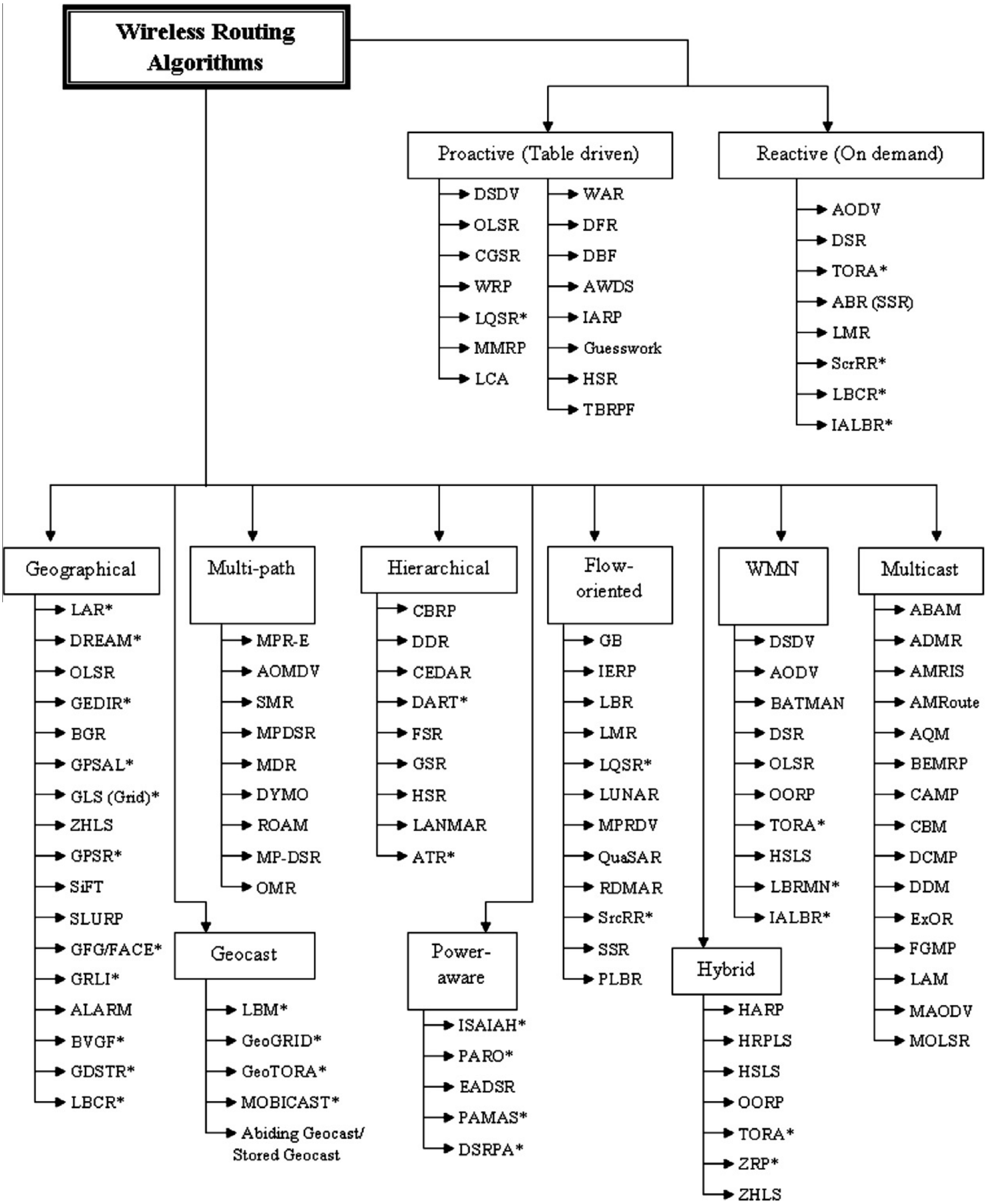

Fig. 3. A structure of routing-algorithm categories. Note that, in this survey, only RAs with asterisk will be discussed in detail. The rest of the RAs are included in this figure to give the reader more information and direct references for alternative RAs and solutions under each category.

1.8. Survey organization

In this survey, we cover a large number of recently-proposed routing protocols in different categories. In addition to the categories that have been discussed in the previous surveys, we investigate some new categories; therefore, the discussed categories are related to different dimensions.

The survey is organized as follows. In Section 2, we discuss the different dimensions of the available routing-algorithm categories associated with the advantages and

Table 1
Routing algorithms taxonomy table (sorted alphabetically).

ABAM [110]	On-Demand Associativity-Based Multi-cast
AGC/SGC [82]	Abiding Geo-cast/Stored Geo-cast, Time-Stable Geo-casting
ABR [109]	Associativity-Based Routing
ADMR [56]	Adaptive Demand-Driven Multi-cast Routing
ALARM [14]	Adaptive Location Aided Routing Protocol - Mines
AMRIS [119]	Ad-Hoc Multi-cast Routing protocol utilizing Increasing id-numberS
AMRoute [81]	Ad-Hoc Multi-cast Routing Protocol
AODV [92]	Ad-Hoc On-demand Distance Vector Routing Protocol
AOMDV [84]	Ad-Hoc On-demand Multi-path Distance Vector Routing
AQM [17]	Ad-Hoc QoS Multi-cast
ATR [18]	Augmented Tree-based Routing
AWDS [124]	Ad-Hoc Wireless Distribution Service
BATMAN [125]	Better Approach To Mobile Ad hoc Networking
BEMRP [88]	Bandwidth-Efficient Multi-cast Routing Protocol
BGR [117]	Blind Geographic Routing
BVGF [120]	Bounded Voronoi Greedy Forwarding
CAMP [41]	Core-Assisted Mesh Protocol
CBM [123]	Content Based Multi-cast
CBRP [59]	Cluster Based Routing Protocol
CEDAR [103]	Core Extraction Distributed Ad-Hoc Routing
CGSR [25]	Cluster-head Gateway Switch Routing protocol
DART [35]	Dynamic Address Routing
DBF [12]	Distributed Bellman-Ford Routing Protocol
DCMP [28]	Dynamic Core Based Multi-cast Routing Protocol
DDM [57]	Differential Destination Multi-cast
DDR [87]	Distributed Dynamic Routing Algorithm
DFR [73]	Direction Forward Routing
DREAM [9]	Distance Routing Effect Algorithm for Mobility
DSDV [93]	Dynamic Destination-Sequenced Distance Vector routing protocol
DSR [63]	Dynamic Source Routing
DSRPA [29]	Dynamic Source Routing Power-Aware
DYMO [21]	Dynamic MANET On-demand Routing Protocol
EADSR [16]	Energy Aware Dynamic Source Routing Protocol
FGMP [24]	Forwarding Group Multi-cast Protocol
FSR [42]	Fisheye State Routing protocol
GB [40]	Gafni-Bertsekas
GDSTR [74]	Greedy Distributed Spanning Tree Routing
GEDIR [107]	Geographic Distance Routing
GeoGRID [77]	Geographical GRID
GeoTORA [68]	Geographical TORA
GFG/FACE [15]	Greedy FACE Greedy
GLS [76]	Geographic Location Service
GPSAL [19]	GPS Ant-Like Routing Algorithm
GPSR [64]	Greedy Perimeter Stateless Routing
GRLI [97]	Geographic Routing without Location Information
GSR [23]	Global State Routing protocol
Guesswork [91]	Guess Work
HARP [86]	Hybrid Ad-Hoc Routing Protocol
HRPLS [89]	Hybrid Routing Protocol for Large Scale Mobile Ad-Hoc Networks with Mobile Backbones
HSLS [101]	Hazy Sighted Link State routing protocol
HSR [54]	Hierarchical State Routing protocol
IALBR [36]	Interference-Aware Load-Balancing Routing
IARP [49]	Intra-zone Routing Protocol/pro-active part of ZRP
IERP [50]	Inter-zone Routing Protocol/reactive part of ZRP
ISAIAH [78]	Infra-Structure Aodv for Infrastructured Ad-Hoc networks
LAM [58]	Lightweight Adaptive Multi-cast
LANMAR [43]	Landmark Routing Protocol for Large Scale Networks
LAR [67]	Location-Aided Routing protocol
LBCR [94]	Load-Balancing Curveball Routing
LBM [69]	Location Based Multi-cast
LBR [83]	Link life Based routing
LBRMN [121,122]	Load-Balancing Routing for Mesh Networks
LCA [44]	Linked Cluster Architecture
LMR [26]	Lightweight Mobile Routing protocol
LQSR [30]	Link Quality Source Routing
LUNAR [113]	Lightweight Underlay Network Ad-Hoc Routing
MAODV [99]	Multi-cast Ad-Hoc On-Demand Distance Vector routing
MDR [33]	Multi-path on-Demand Routing
MMRP [47]	Mobile Mesh Routing Protocol
MOBICAST [53]	Mobile Just-in-time Multicasting

Table 1 (*continued*)

MOLSR [70]	Multi-cast Optimized Link State Routing
MP-DSR [75]	Multi-Path Dynamic Source Routing
MPRDV [6]	Multi-point Relay Distance Vector protocol
MPR-E [100]	Multi-Path Routing with EAPAR
OLSR [55]	Optimized Link State Routing Protocol
OMR [61]	On-demand Multi-path Routing
OORP [126]	Order-One Routing Protocol
PAMAS [102]	Power-Aware Multi-Access Protocol with Signaling
PARO [46]	Power-Aware Routing Optimization Protocol
PLBR [104]	Preferred link based routing
QuaSAR [115]	QoS aware source initiated Ad-Hoc routing
RDMAR [4]	Relative-Distance Micro-discovery Ad hoc Routing protocol
ROAM [96]	Routing On-demand Acyclic Multi-path
SiFT [20]	Simple Forwarding over Trajectory
SLURP [118]	Scalable Location Update-Based Routing Protocol
SMR [72]	Split Multi-path Routing
SrcRR [5]	Source Routing for Roofnet
SSR [32]	Signal Stability Routing protocol
TBRPF [10]	Topology Dissemination based on Reverse-Path Forwarding routing protocol
TORA [90]	Temporally-Ordered Routing Algorithm routing protocol
WAR [8]	Witness Aided Routing
WRP [85]	Wireless Routing Protocol
ZHLS [62]	Zone-based Hierarchical Link State routing
ZRP [48]	Zone Routing Protocol

disadvantages of each category. Then, in Section 3, we discuss the main wireless issues and analyze methods that are used by some routing algorithms to solve these issues. Section 4 concludes the paper with a summary of our contributions.

2. Categories of routing algorithms

The early routing algorithms (RA) for wireless networks are classified, similar to those for wired networks, according to centralized/distributed and proactive/reactive categories. However, in recent years, the wireless routing algorithms in the literature have evolved to encompass the unique challenges posed by wireless networks, which, in turn, introduce several novel routing categories, as shown in Fig. 3 (and accompanying Table 1). In this survey we focus on Geographical, Geo-casting, Hierarchical, Multi-path, Power-aware, and Hybrid routing algorithms.

In this section, we discuss the characteristics, advantages, and disadvantages of each routing-algorithm category. The routing-algorithm examples under each category are shown in Fig. 3. We start with the traditional or classical dimensions of categorizing the routing algorithms which includes the Proactive RA and the Reactive RA. Then, we demonstrate new dimensions of categorizing the routing algorithms which match the wireless network characteristics. The new dimension categories include Geographical RA, Geo-casting RA, Hierarchical RA, Multi-path RA, Power-aware RA, and Hybrid RA.

2.1. Proactive RA [51,80]

Proactive (or table-driven) routing is an approach where each router can build its own routing table based on the information that each router (or node) can learn by exchanging information among the network's routers. This is achieved by exchanging update messages between routers on a regular basis to keep the routing table at each router up-to-date. Then, each router consults its own routing table to route a packet from its source to its destination. When a source node (or an intermediate node) consults the routing table, the path information, which is up-to-date, is immediately available and can be used by the node. This is because each router (or node) in the network periodically updates routes to all reachable nodes via broadcasting messages that the node received from the other nodes in the network.

In a Proactive RA, although getting the path information is fast, the maintenance of the up-to-date network information requires high overhead traffic and needs some significant amount of bandwidth. In addition, the process of maintaining the routes to the reachable nodes is continuous even if there is no data traffic flowing on these routes.

2.2. Reactive RA [51,80]

Reactive (or on-demand) routing is an approach where the routing process needs to discover a route whenever a packet arrives from a source and needs to be delivered to a destination. Here, each node has no pre-built routing table (or global information) to be consulted. Due to the node's mobility in a wireless network, maintaining the existing route is an important process.

In a Reactive RA, the route discovery process happens more often, but this process requires low control overhead traffic compared to the Proactive RA. Therefore, the Reactive RA is considered to be more scalable than the Proactive RA [80]. In addition, using a Reactive RA, the node has to wait for the discovery process each time the node attempts to send a message; this increases the overall delay.

2.3. Geographical RA [2,3,38,45,106]

A major evolution in communication technology has been the introduction of the Global Positioning System (GPS) which provides the location information and universal timing of a node. The idea of Geographical routing is based on the following: a sender uses the destination's geographic location to deliver a message. The location information can be used instead of the network address in the routing process. Therefore, it is not essential for the sender, in Geographical routing, to be fully aware of the network topology. Additionally, Geographical routing assumes that each node knows its own location and each source is aware of the location of its destination. In fact, this idea of using position information for routing is not new; in the 1980s, the geographic information was proposed for packet radio networks [108].

In Geographical routing, there are three main strategies: single-path, multi-path, and flooding. In single-path, one copy of the message travels through the network over a single defined route from the source node to the destination node. On the other hand, flooding broadcasts the message which creates a large number of copies of the original message traveling through the network. Since single-path and flooding are the two extremes strategies, multi-path is a compromise solution in which a small number of copies of the original message is created and transmitted on different routes from the source node to the destination node. Most single-path Geographical RAs are based on two techniques: Greedy Forwarding (GF) [116] and face routing [15] (detailed descriptions of GF and Face routing are provided in Sections 3.2 and 3.2.1, respectively). The routing algorithms that rely on flooding develop enhanced techniques to overcome the limitations of flooding. The enhancement techniques will be discussed in Section 3.

In a wireless network, the Geographical location information can improve routing performance. Using localization algorithms,[6] the network overhead is reduced. Moreover, most Geographical RAs are scalable and fault tolerant (e.g., GLS [76]). However, instantaneous location information may not be accurate at the time the information is needed. In addition, the assumption of all nodes knowing their location may not be realistic. Therefore, the network efficiency depends on balancing the geographic distribution *versus* occurrence of traffic bottlenecks.

Most Geographical RAs start with the GF technique to find the route for a packet from its source to its desired destination. The main problem with the GF technique is that there could be a certain point where a node (say node A) has no surrounding neighboring nodes within its transmission distance closer to the destination node more than node A itself. Because of this problem, most Geographical RAs include a recovery method to handle the routing process when such cases occur. Flooding in LAR [67], planarity and face in GPSR [64], hull tree in GDSTR [74], grid in GLS [76], partitioning to subgraphs in BVGF [120], and heuristics in GEDIR [107] are alternative recovery methods to accomplish the routing.

2.4. Geo-cast RA [60,82]

Geo-cast is the process of sending a message in a network from a source to a group of destinations by using only their geographical location information. Therefore, Geo-casting merges between the concept of multi-casting (single source to multiple destinations) and the concept of geographical location (routing is based on the nodes' locations) The geographical region is the area where the set of destinations is located. A destination's location, which presents the destination location address, can take different shapes such as a point, a circle, or a polygon. This type of routing is used for Ad-Hoc networks.

In Geo-cast RA, geographic routing nodes are called Geo-Router. Each Geo-Router can determine its geographic service area.[7] Geo-Routers maintain their routing table by exchanging service-area information among neighbors. These routers are organized in a hierarchy. The advantages and disadvantages of Geo-casting RA are similar to geographical routing protocols.

Geo-casting RA can be used to create the additional intelligent step that we might need to develop a new protocol that deals with exchanging control packets while using a traditional RA to route data packets. This can be useful if we employ an intelligent link-aware routing metric for wireless networks.

2.5. Hierarchical RA [2,3,52,80]

In Hierarchical routing, nodes are organized into groups called zones or clusters. Each cluster has one or more cluster heads and gateways. The cluster head is responsible to maintain the connectivity of all nodes within its cluster. The gateway is the access point between two neighboring clusters; hence, the gateway can communicate with more than one cluster head, which belong to different clusters. However, nodes, which are not gateways, can only communicate with the cluster heads that belong to the node's cluster. Nodes in a cluster are either directly connected to or within few hops from the cluster head. In the cluster environment, different mechanisms can be used for intra-cluster routing (routing within a cluster) and inter-cluster routing (routing between clusters). For instance, proactive approach can be used for inter-cluster routing and reactive approach can be used for intra-cluster routing. In a Hierarchical RA, failures and topology changes can be fixed easily because only the intra-cluster update messages are considered by the cluster nodes. Therefore, only the cluster that has failures or topology changes is affected by these issues while the other clusters that have no failure, which are part of the whole network, are not affected by the intra-cluster failures and topology changes. Hierarchical routing provides an approach for scalability. However, whether or not these hierarchical schemes can really solve the scalability problem still remains a question [2,52].

Hierarchical routing and cluster-based routing are studied in different surveys such as [52,80]. Although some surveys distinguish between Hierarchical routing and cluster-based routing, we believe that these two routing approaches are relevant and can be discussed under the

[6] Localization is an algorithm used by any network node to determine the node's position based on the predefined information of specific reference nodes in the network.

[7] Geographic service area is the union of geographic areas that are attached to a Geo-Router; in other words, the geographic service area is a set of geographic areas that surround the Geo-Router and is served by this Geo-Router.

Hierarchical routing approach. In the cluster-based approach, the functionality of cluster heads and gateways in cluster-based approach splits the structure of the network into two tiers: high-level tier (which includes the cluster heads) and low-level tier (which includes the nodes). This structure is hierarchical which justifies this vision.

Hierarchical routing's advantage depends on the depth of nesting (number of hierarchy levels) and the addressing scheme used (such as the assigned IDs for each level). In a high-density network, the performance of Hierarchical routing is considered to be very good compared to other routing approaches. The reasons of this good performance are: low overhead, relatively short routing paths, easy adaptation to failures, and quick path-setup time achieved by Hierarchical routing.

While designing the structure of the hierarchy, the cluster heads should be carefully selected to avoid having a bottleneck and to avoid large power consumption. A WMN may experience implementation difficulties when the selected cluster head is not capable to handle the heavy traffic load. Additionally, the complexity of maintaining the hierarchy may compromise the performance of the routing protocol.

2.6. Multi-path RA [2,3,112]

In Multi-path routing, multiple paths can be used to route data from a source to its destination. The utilization of the available network resources might be increased which makes a network more tolerant to failure, more balanced, utilizing more aggregate bandwidth, and requiring less delay by cutting down on the time to discover a new route when a failure occurs. Path discovery (using a predefined criteria to find available paths between source–destination pairs), path disjointedness (using a path-disjointedness metric to evaluate the diversity of the paths), traffic distribution (a method of available path utilization and load distribution among these paths for a source–destination pair), and path maintenance (a strategy to be followed when the status of the available paths changes) are the main elements of Multi-path RAs.

A Multi-path RA has the following advantages: first, fault tolerance, which is achieved by using redundant paths as alternative routes exist to deliver messages from a source to its destination. Second, when a link becomes a bottleneck because of heavy load at a specific time, Multi-path RAs can balance the load by diverting traffic through the available alternative paths. Third, Multi-path RAs can split data to the same destination into multiple streams, each routed through a different path, to increase the aggregate bandwidth utilization of a network. Fourth, in Multi-path RAs, the recovery delay in case of a fault could be reduced because backup routes are initiated during the route discovery phase. Thus, when a failure occurs, a Multi-path RA can use the predefined routes instead of rediscovering a new route. Because of the critical effect of delay in a wireless network, this property of Multi-path routing is better suited to match the needs of the wireless network environment.

On the other hand, given a performance metric, the improvement of Multi-path RA depends on the availability of disjoint routes between source and destination. Moreover, the complexity of the Multi-path RA (especially for the route-discovery phase) can be high.

2.7. Power-aware RA [114]

In a wireless network, due to node mobility, the power issue is one of the critical topics that has attracted both academic as well as industry researchers. For a mobile node, the battery lifetime controls the amount of mobility time that this node can have. Consuming more power means reducing the battery lifetime; in other words, longer mobility time means more power consumption of the node's battery. Thus, a good wireless routing approach should tradeoff between power consumption and mobility. To reduce power consumption, different strategies have been proposed by each Power-aware RA, which are listed in Fig. 3. We will discuss these strategies in Section 3.

Signal transmission energy is proportional to the distance between a sender and its receiver. The relation between energy and distance can be written as: $E \approx d^{\alpha}$, where E is the energy, d is the distance, and α is the attenuation factor or path-loss exponent. The value of α depends on the transmission medium ($\alpha \geqslant 2$) [98], e.g., $\alpha = 2$ in the free-space environment which is considered as the optimal case.

2.8. Hybrid RA [80]

In a Hybrid RA, routing starts with a proactive approach and then the algorithm serves the demand from additionally-activated nodes through reactive flooding. Hybrid RAs reduce the control overhead of proactive routing protocols and decrease the latency caused by route discovery in reactive routing protocols.

A Hybrid RA is a subset of the adaptive routing approaches where the assignment of proactive/reactive routing is developed alternatively based on the instantaneous network characteristics.

In an Ad-Hoc network, a Hybrid RA can be implemented in a hierarchical network architecture. The performance of the network depends on the distribution of the proactive/reactive approaches for each level of the network hierarchy. This type of protocol combines the advantages of proactive and reactive routing.

3. Issues in routing techniques

Basic routing algorithms, such as Dynamic Source Routing (DSR) [63] and Ad-Hoc On-demand Distance Vector (AODV) [92], were implemented to forward data packets from a source to a destination. Developing a routing algorithm for a wireless network should consider the distinct wireless-physical characteristics. Therefore, new techniques can be used to avoid issues such as large area of flooding, empty set of neighbors (when Greedy Forwarding (GF) technique [116] is used), flat addressing, widely-distributed information, and large power consumption.

In this section, we present the issues faced by various routing algorithm that are avoided by the proposed routing

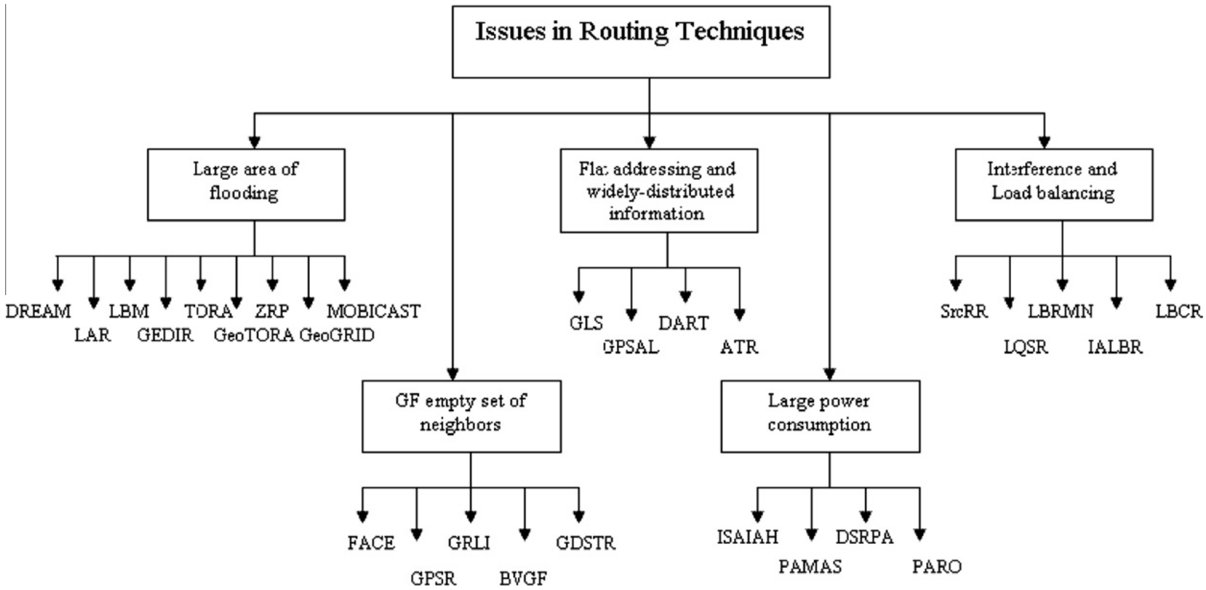

Fig. 4. Representative sample of routing algorithms discussed in Section 3.

algorithms for wireless networks. We also discuss the different methods that are used by each routing algorithm to enhance the original routing technique, such as flooding, GF, flat,[8] and non-power-aware routing. Fig. 4 shows the issues discussed in this section and lists the routing algorithms that developed different techniques to solve these issues. This survey considers the representative sample of routing algorithms listed in Fig. 4.

3.1. Large area of flooding

Flooding is a routing technique that is used during the route-discovery phase or as a recovery method to deliver a message from a source to a destination. Flooding works as follows: when a source node (S) needs to send a data packet to a destination node (D), node S broadcasts a route-request message to all of its neighbors (nodes that are within node S's transmission range) looking for node D. A neighbor node (N) (representing any intermediate node) checks if the route-request message is sent to itself; if not, node N broadcasts the data packet to node N's neighbors. This process is repeated until the route-request message reaches node D. To avoid duplicate transmissions of a route-request message, each node checks the sequence number of the arrived route-request message and compares this number to the stored (or buffered) sequence number, which is related to the node's last forwarded route-request message; any arrived route-request message with a smaller sequence number than the stored sequence number is discarded by the node. Since the path of the route-request message is stored in the message header, node D can reply to node S by a route-reply message using the reverse stored path. Timeout is used by the source to detect a possible packet loss and to resend the route-request message.

Flooding is a reliable technique because, if the network is connected, the data packets are delivered from a source to a destination with high probability. In addition, flooding guarantees that, from any node, all other nodes in the network are reachable. Packet overhead and inefficient bandwidth utilization are two of the main disadvantages of flooding-based routing.

In the following routing algorithms, we describe different flooding-based methods that are used to reduce the size of the flooding area and to overcome flooding's basic problems.

3.1.1. Distance Routing Effect Algorithm for Mobility (DREAM)

DREAM [9] is a proactive geographical routing protocol which reduces the flooding-area size by limiting the number of neighbors who can forward (or broadcast) a route-request message (RRQST). DREAM is also considered to be a distributed, loop-free, robust, and multi-path routing protocol. Based on the distance effect and mobility rate principles in a wireless network, DREAM controls both the routing update frequency and message lifetime to minimize the routing overhead. In distance effect, the distance between a pair of nodes is used to decide how important this pair of nodes appear to each other; for instance, when this distance is large, the movement of these nodes appears to be slow with respect to each other. Therefore, nodes that are positioned closely receive updates more frequently from each other. The mobility rate of each node determines the frequency of advertising the node's new location; i.e., a node sends more updates when the node travels with high speed because this node changes its location more frequently. This feature allows DREAM to efficiently utilize both bandwidth and energy.

Each node periodically broadcasts its location information to all other nodes in the network via a control packet.

[8] Flat routing is used to exchange information in a flat way, i.e., no hierarchy structure is used to collect the node's information.

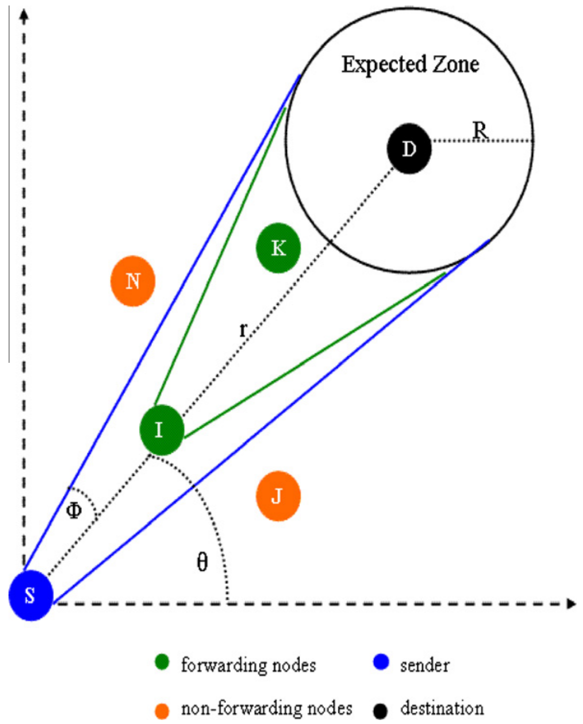

Fig. 5. DREAM's Expected Zone and the predetermined flooding area from source node S to destination node D. Nodes I and K, which are located in the direction of node D's Expected Zone, forward the received packet from node S, whereas nodes J and N do not forward. α and ϕ are the angles which are used by node S to calculate the flooding area.

DREAM uses location information to adapt mobility in a wireless network. The available location information is stored and maintained in a node's location table. While routing a data packet, nodes located in the direction of the destination (which is predetermined by the source node) are the only nodes which can forward this data packet. Hence, in DREAM, data packets are partially flooded to a subset of the one-hop neighbors of each intermediate node. Fig. 5 illustrates the range of nodes which are allowed to forward the data packets from node S to node D. Therefore, node I and node K can forward the received packets because node I and node K lie on the direction of node D and within the range $[\theta - \phi, \theta + \phi]$. Because node D is a mobile node, the Expected Zone of radius 'R' is used to show the movement range of the destination. When a node has an empty neighbor set, DREAM recovers by flooding the data packet to the entire network. When flooding is used to deliver a data packet, the destination does not send an Acknowledgement (ACK) message to the source.

3.1.2. Location-Aided Routing (LAR)

LAR [67] is a Geographical routing algorithm and an alternate on-demand source-routing algorithm, which limits the area for discovering a new route to a smaller "request zone" by utilizing the node's location information. Thus, the number of route-request messages is reduced. LAR is an enhanced flooding-based protocol used in on-demand algorithms such as DSR [63] and AODV [92]. There are two schemes of LAR (Scheme 1 and Scheme 2), as

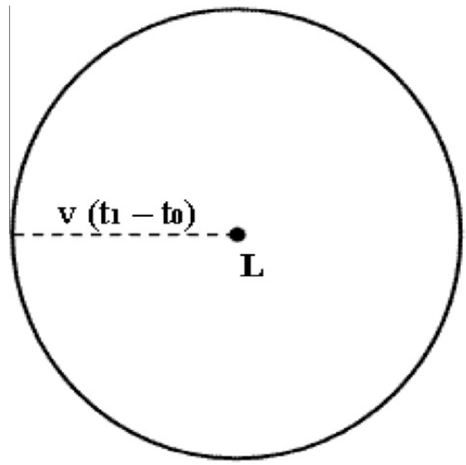

Fig. 6. LAR Expected Zone, where L is the initial location of D [67].

shown in Fig. 7. Both are based on zone calculation such as Expected Zone and Request Zone, as shown in Figs. 6 and 7(a), respectively. The relation between Expected Zone and Request Zone is as follows:

- Based on its previous knowledge, the sender node (S) can calculate the Expected Zone at time t_1 by using the (X_d, Y_d) coordinates of the destination (D) as well as the average speed of D (v) that S collected at time t_0 where $t_0 < t_1$.
- The Expected Zone is the circle around the (X_d, Y_d) point with radius $(R) = v * (t_1 - t_0)$, as shown in Fig. 6; if there is no mobility, the radius of the Expected Zone is zero which means the Expected Zone is only one point (X_d, Y_d).
- The Request Zone uses the information of the Expected Zone; the Request Zone is the rectangular area that includes the Expected Zones of both nodes D and S, which is shown in Fig. 7(a).
- S knows the corner coordinates of the Request Zone. This is used as a limitation to the flooding protocol in such a way that any node outside this rectangle, such as node N in Fig. 7(a), is not forwarding the received route-request message (RRQST) that is initiated by S; otherwise, the node forwards RRQST, such as nodes I and K. The route-request message is the probe message (used in source-routing algorithms) that is initiated by a source to discover the route to the desired destination.
- Unlike the flooding protocol, in case of LAR, all neighbors forward the request.

The previous description can be used for Scheme 1. Scheme 2 uses the same information of D at node S, but this time the location information is implicitly included in the route-request message. In Fig. 7(b), define a variable called $DIST_s$ which is the distance from (X_d, Y_d) to (X_s, Y_s), where (X_s, Y_s) are the coordinates of node S. $DIST_s$ and (X_d, Y_d) are included in the message. An intermediate node i calculates $DIST_i$ of node i's distance to (X_d, Y_d); if $DIST_s < DIST_i$, then node i discards the message; otherwise, node i forwards the message after $DIST_i$ replaces $DIST_s$.

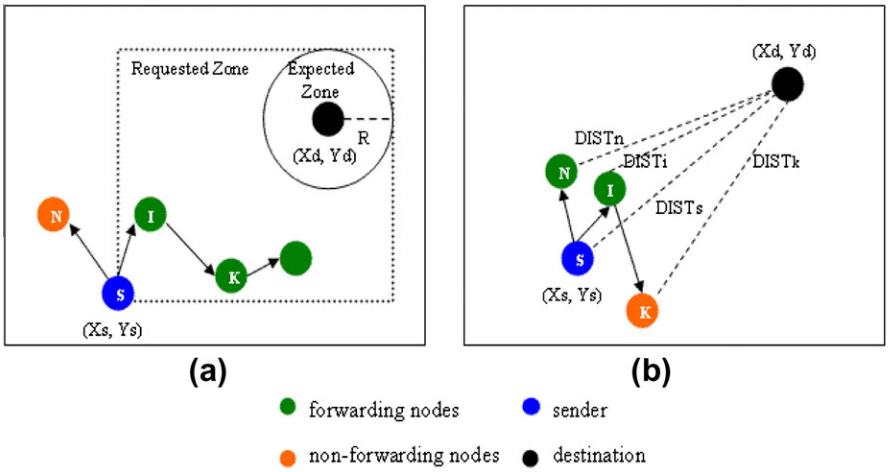

Fig. 7. (a) LAR Request Zone of Scheme 1 and (b) LAR Scheme 2 [67].

Table 2
Examples of Scheme 1 and Scheme 2 of LAR referenced to Fig. 7(a) and (b).

Node	Scheme 1	Scheme 2
N	Discard	Forward
I	Forward	Forward
K	Forward	Discard

Table 2 shows the results of the LAR algorithm and how LAR decides to select the next-hop node based on the node's location. For instance, in Scheme 1, nodes I and K forward the received RRQST to their neighbors because nodes I and K are inside the Request Zone of node S while node N in Scheme 1 discards the received RRQST since node N is outside the Request Zone of node S. On the other hand, in Scheme 2, nodes N and I forward the received RRQST if the distances $DIST_n$ and $DIST_i$ are shorter that $DIST_s$. But node K discards the RRQST because $DIST_s < DIST_k$.

Scheme 1 can be modified to account for location-estimation error by changing the value of R to $e + v * (t_1 - t_0)$, where e is the maximum location error, while Scheme 2 may suffer from high values of error (e).

LAR reduces the overhead caused by the original flooding protocol, but LAR does not include the location error while testing the algorithm. LAR also ignores the transmission error congestion, and simultaneous attempts of multiple nodes. In general, Scheme 2 performs better than Scheme 1. For evaluation, MaRS, which is a modified version of NS-2, has been used to compare LAR vs. a flooding-based protocol [67].

Scheme 1 is a good choice for an Ad-Hoc network but not for a fixed WMN because its core idea is based on the average speed of mobile nodes. Therefore, for a WMN, an algorithm with more emphasis on fixed nodes is needed. Thus, Scheme 2 is compatible with the nature of a WMN.

3.1.3. Location Based Multicast (LBM)

LBM [69] is a geo-cast routing algorithm which is similar to LAR in the concept of limiting the flooding-area size. LBM has two schemes:

- Scheme 1: Definition of Forwarding Zone (FZ) is as follows:
  - If a node in FZ receives a packet, this node forwards the packet to its neighbors; and
  - if a node OUTSIDE of the FZ receives a packet, this node discards the packet.
- Scheme 2: No explicit Forwarding Zone. This scheme determines whether a packet should be forwarded based on the relative distance between the nodes.

The notion of multicasting in LBM is based on the number of destinations. In LAR, there is only one destination node, while in LBM, the sender sends a packet to multiple receivers (destinations) associated as one group. LBM provides high accuracy (ratio of the number of multicast group members which actually receive the multicast packet and the number of group members which were supposed to receive the packet) and lower overhead (number of multicast packets) compared to multicast flooding.

3.1.4. Geographic Distance Routing (GEDIR)

GEDIR [107] is one of the first Geographical RAs; its objective is very basic. Each node is assumed to know its own location, its neighbor locations, and the destination location. The approach of GEDIR can be summarized in the following example. When a source node (node S) wants to send a data packet to a destination node (node D), node S forwards the data packet to its geographically-closest neighbor node to node D, which is node K as shown in Fig. 8. Node K, in this case, is the neighbor that has the best progress towards node D among all neighbors of node S. Additionally, node K is the closest directional neighbor which is located in the direction of node D. This process is repeated at each intermediate node until node D is reached.

GEDIR acts similar to the Greedy Forwarding algorithm to limit the number of forwarding nodes and it overcomes the problems of flooding. On the other hand, using GEDIR, GF can be also improved by allowing a message to travel in backward direction for one hop (i.e., a message is dropped only if the message has to be sent back to the node of the

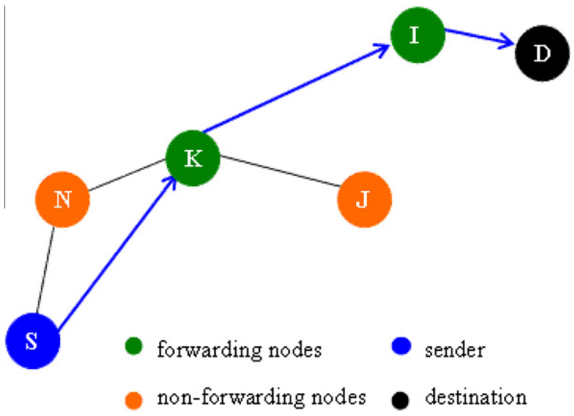

Fig. 8. GEDIR example.

previous forwarding step). Furthermore, the delivery rate of GF can be increased if each node is aware of its two-hop neighbors. However, GEDIR faces some challenging issues, especially when a node cannot be reached by any other node in the network. This problem occurs when the closest neighbor has no route to the destination.

3.1.5. Temporally-Ordered Routing Algorithm (TORA)

TORA [90] is an adaptive/hybrid routing algorithm that is designed to minimize reaction to topological changes by localizing routing-related messages to a small set of nodes near the change. In TORA, routing from a source node to a destination node requires a sequence of directed links starting at the source and ending at the destination. Each intermediate node maintains a height which is measured based on the number of hops separating the intermediate node from the destination node. A Directed Acyclic Graph (DAG)[9] rooted at the destination is used to assign the height for each node. Each node in the network maintains a logical direction for its links using the height value. The direction of the logical links is from a node with higher height value to a node with lower height value.

Fig. 9(a) illustrates the network topology, and Fig. 9(b) shows the DAG creation phase in TORA; in Fig. 9(b), arrows on each wireless link points from the higher-height node to the lower-height node, which means that a data packet is forwarded to a neighbor with lower height than the forwarding node's height. The height of each node represents the number of hops that separate the node from the destination node. When the DAG is completed, each node in the network has a route to the destination. Each intermediate node can reuse the height information, which the node stored, for later connections to measure the distance from itself to previously-connected destinations. This stored information can speed up the process of creating the next DAG.

3.1.6. Geographical TORA (GeoTORA)

In the previous subsection, we described the uni-cast routing protocol 'TORA' [90] which is an Ordered Routing Algorithm. In this subsection, we introduce a geo-cast routing algorithm called GeoTORA [68] which is a variation of TORA. Unlike TORA, GeoTORA broadcasts a message to a group of destinations where a source node essentially performs any-cast to any geo-cast group member via the TORA routing protocol.

In Fig. 10, an example of the GeoTORA operation is given. Similar to TORA in Figs. 9, 10(a) shows the initial network topology, and Fig. 10(b) shows the final DAG. Note that the number on each node, in Fig. 10(b), is the height of that node.

GeoTORA has small overhead and high accuracy, but not as high as pure flooding or LBM. There are other proposals that suggested other Geo-PROTOCOLs, using other unicast routing protocols (e.g., DSR, AODV), to replace TORA [60].

3.1.7. Geographical Grid (GeoGRID)

GeoGRID [77] is a geo-cast routing algorithm that enhances the forwarding idea of LAR in the geographical routing protocols by reducing the network overhead. GeoGRID logically reduces the flooding area of the broadcasting messages. GeoGRID takes its name from the process of partitioning the geographical area of the network into smaller areas, called grids. These grids are logical and have the same size. In each grid, one node, which is the closest to the grid center, is elected as a gateway to forward the geo-cast packets among the neighboring grids. Hence, message overhead decreases because, in each grid, non-gateway nodes do not broadcast the grid packets. In GeoGRID, designing the grid size is important to achieve network connectivity through the assigned gateways.

Fig. 11 shows an example of this algorithm. This example considered only the gateway nodes (i.e., all intermediate nodes are gateways). In Fig. 11(a), Scheme 1, a rectangular forwarding region is defined. Each node inside the forwarding region forwards the packet by means of broadcast, that is, the packet may reach nodes outside the forwarding region. However, these nodes drop the packet instead of rebroadcasting it. In Fig. 11(b), Scheme 2, the initial sender has distance 10 to the center of the destination region. The distance is included in the geo-cast packet. Nodes receiving the initial broadcast calculate their own distance to the destination region. If their distance is not larger than the distance included in the received packet, the packet is rebroadcast. Otherwise, the packet is discarded.

GeoGRID has advantage over LBM when the network is crowded (network with a large number of nodes) because, in GeoGRID, only the gateway is responsible to forward the packets. Hence, GeoGRID reduces the overhead compared to LBM. In addition, GeoGRID has lower delivery cost (in terms of packet delay) than LBM.

[9] A Directed Acyclic Graph (DAG) is used in TORA as an initial step to calculate the height of each neighbor. The DAG is created as follows. A source node broadcasts a route-request message to all neighbors to find a route to a destination. The route-request message is rebroadcasted until the DAG is created. This is based on the height value of each node that maintains the directions of the DAG's arrows. On receiving a route-request message, each node broadcasts its height to its neighbors. Although DAG is based on flooding, the routing process after the first step, which is creating the DAG, relies on the fact that only the nodes with lower height are allowed to rebroadcast the received packets.

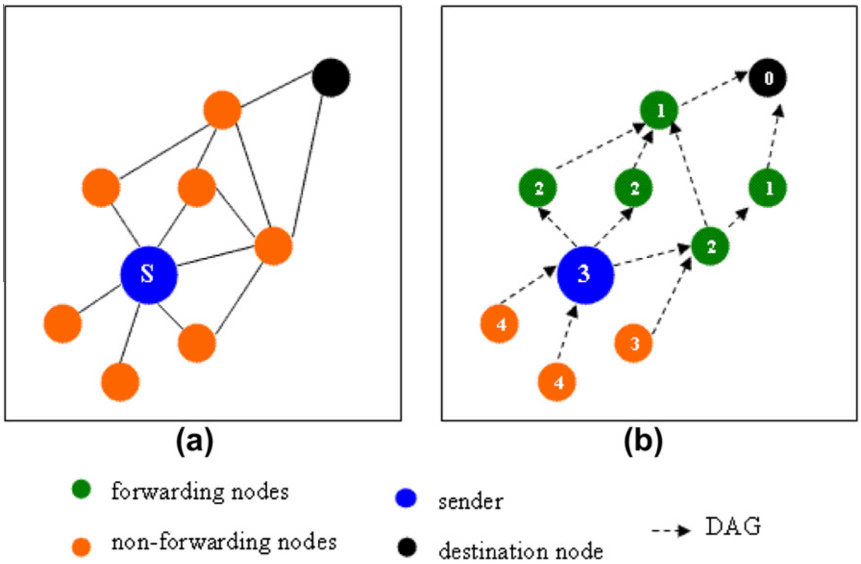

Fig. 9. TORA example: (a) Network topology and (b) DAG with height value of each node in the network towards the destination node.

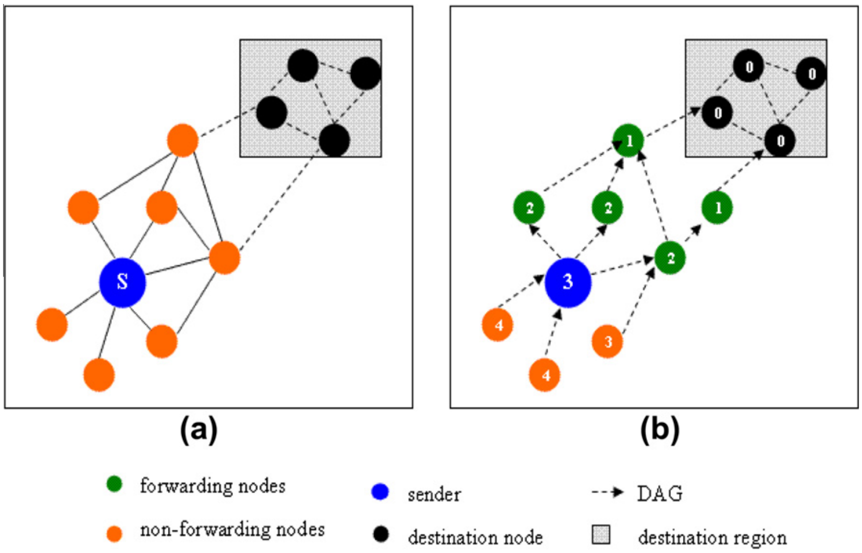

Fig. 10. GeoTORA example: (a) Network topology and (b) DAG with height value of each node in the network towards the destination region.

3.1.8. Zone routing protocol (ZRP)

ZRP [48] is a hybrid/hierarchical routing protocol with both proactive and reactive routing components. ZRP creates overlapped zones based on the separation distances between mobile nodes. For instance, each node i, given a hop distance (h), can create its own routing zone, which consists of node i's neighbors located at most h hops away from node i. Neighbors, which are exactly h hop away from node i, are called peripheral nodes. Peripheral nodes are the only nodes within a routing zone allowed to rebroadcast the control messages to nodes that are located outside that zone. Hence, ZRP limits the flooding area in the wireless network. Fig. 12 illustrates an example of node i's zone and peripheral nodes.

In ZRP, two routing approaches are used: Intra-zone Routing Protocol (IARP) [49] and Inter-zone Routing Protocol (IERP) [50]. IARP is a proactive approach that routes packets within each routing zone (when a source and its destination belong to the same routing zone). But IERP is a reactive approach that routes packets between different routing zones (when a source and its destination belong to different routing zones).

3.1.9. Mobile Just-in-time Multicasting (MOBICAST)

MOBICAST [53] is a topology-aware geo-cast routing algorithm that addresses space–time restrictions on the multicast recipient set. MOBICAST routing process considers two main zones: a delivery zone and a forwarding zone.

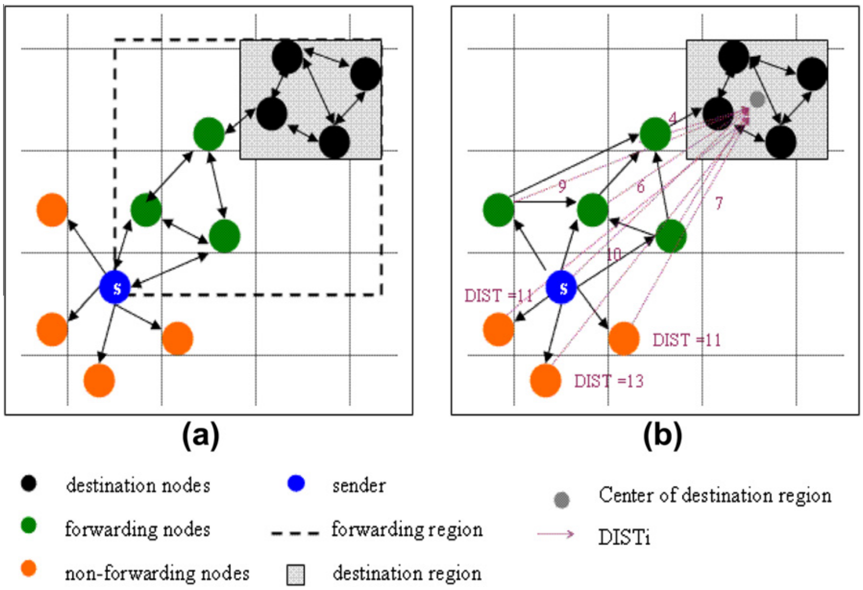

Fig. 11. GeoGRID example.

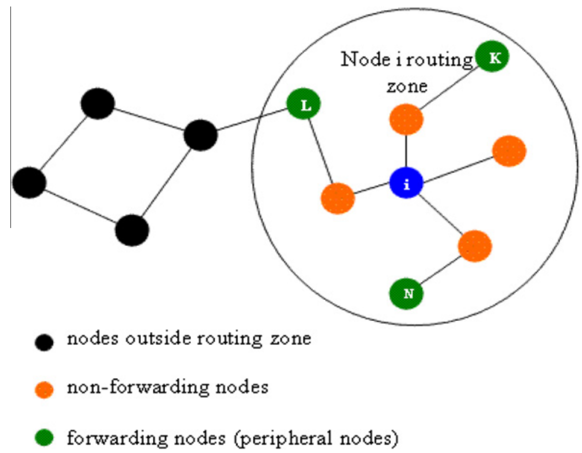

Fig. 12. ZRP example: the selected hop distance is 2; thus, the peripheral nodes are located 2 hops away from node i. The routing zone of node i contains 1-hop and 2-hop neighbors.

The application specifies the delivery zone, which is the area of the destinations which are guaranteed to receive the broadcasted messages. However, the forwarding zone is the area where nodes are allowed to rebroadcast the received messages. The delivery zone shape and the topology of the network control the shape of the forwarding zone. The headway distance (of a given forwarding zone) is the distance that separates the forwarding zone from the delivery zone. The forwarding zone limits the broadcasting area; hence, MOBICAST is considered as a flooding control routing algorithm.

3.2. Greedy Forwarding (GF) empty set of neighbors

Greedy Forwarding [116] is one of the techniques on which single-path (only one route can be discovered from the source to its destination) routing relies. GF works as follows: when a source node needs to send a data packet to a destination node, the source node forwards the data packet to the geographically-closest neighbor towards the destination among its neighbors. This procedure is repeated at each intermediate node until the destination is reached. Unlike flooding, GF forwards the data packet to a single neighbor instead of broadcasting the packet to all neighbors. However, GF can have a critical issue which we call 'GF empty-neighbor-set problem' where a node cannot find any neighbor which is closer to the destination than itself. Hence, the forwarding process reaches a dead end. Because of this problem in GF, new approaches are proposed as backup techniques to recover from the GF empty-neighbor-set problem. In the following subsections, we present routing algorithms that develop some of these techniques in their forwarding processes.

3.2.1. FACE routing protocol

FACE [15] is a distributed Geographical routing algorithm based on a unit graph[10] (in which two nodes can communicate if the Euclidean distance [34] between them is less than some fixed amount). In FACE, the graph's global information is not required. The name of this algorithm is inspired by the graph-theory concept of planarity where the graph can be viewed as a number of faces. The FACE algorithm is based on two main steps:

(i) Extract a new connected planar graph (a sub-graph of the original network graph) by eliminating all the cross edges from the network graph that inter-

[10] Unit graph is a geometric graph ($G = (V, E)$), where V is the set of vertices and E is the set of edges. Let u and $v \in V$, then an edge $(u, v) \in E$ if and only if the Euclidean distance between node u and node v is less than or equal 1 ($\text{dist}(u, v) \leqslant 1$).

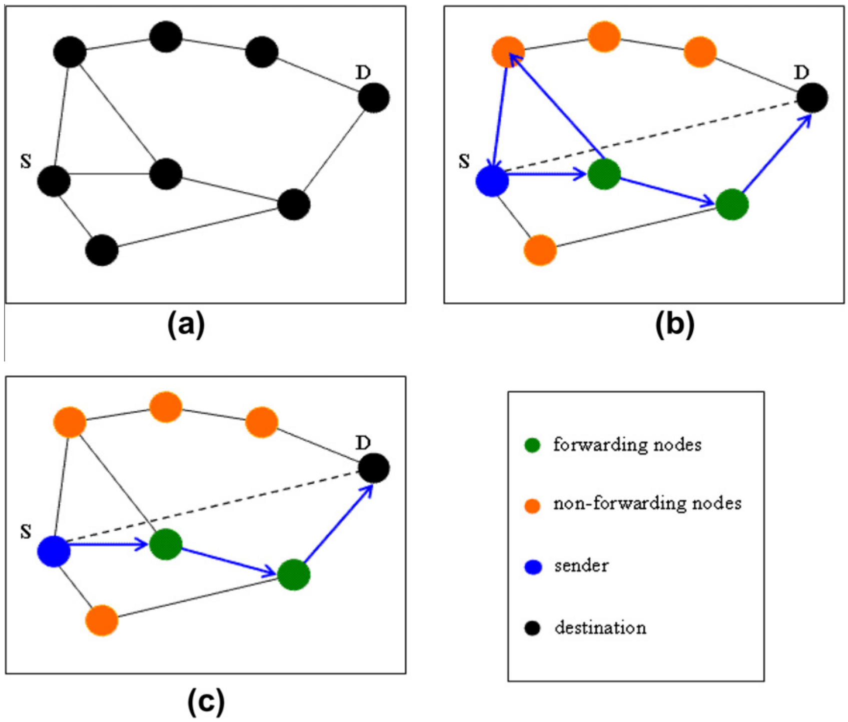

Fig. 13. Example (FACE): (a) Network planar graph, where node S is the source and node D is the destination. (b) Using FACE-1, path from S to D is established by first drawing a line between S and D, and then the packet traverses the faces (all links on each face) that intersect with the line. (c) Using FACE-2, path from S to D is established by first drawing a line between S and D, and then the packet traverses the faces that intersect with the line.

sect using one of the well-known planar graphs such as Gabriel graph (GG) [39] or Relative Neighborhood Graph (RNG)[11] [111].

(ii) Traverse the planar graph using the right-hand rule[12] to find the route from any source to any destination. This is done by drawing a line between S and D, and then traversing all faces counter-clockwise that have edges intersect with the S–D segment. Only the outer face is traversed clockwise.

An improved FACE algorithm (called FACE-2) reduces the number of traversed edges on each face. This is because, in the original FACE algorithm (FACE-1), each face traverses all edges and then leaves the face, but in the improved algorithm, the face is traversed up to the edge that intersects with the S–D segment.

Fig. 13 illustrates an example of routing a data packet from node S to node D using both FACE-1 (Fig. 13(b)) and FACE-2 (Fig. 13(c)). FACE-1, in Fig. 13(b), traverses the first face of the network counter clockwise; then, FACE-1 moves to the second face, which includes the destination node. Therefore, in this example, FACE-1 traverses 5 links and FACE-2 traverses 3 links only. FACE routing technique is used by other routing algorithms, such as GPSR (which will be discussed later), to avoid the issue of GF's empty-set problem.

Although FACE assumes a unit graph, which is not a practical assumption, FACE is reliable and requires no data packet duplication. Both GEDIR [107] and FACE-2 perform closely in terms of packet delivery rate (or throughput). The results in [15] show that the average dilation[13] of GEDIR is consistently low, but this comes at the price of low delivery rate in sparse graphs[14] since number of edges is limited on such graphs.

3.2.2. Greedy Perimeter Stateless Routing (GPSR)

GPSR [64] is a Geographical routing algorithm using direct-neighbor location information in forwarding decisions. GPSR assumes that each node is aware of its own location and the status of its one-hop neighbors. Also the source node is aware of its destination node's location. The one-hop neighbors exchange control messages (called

[11] GG [39] and RNG [111] use two different inequalities that are applied on all edges of the network graph to select only the edges that represent a planer graph; any edge which does not belong to this planner graph fails to satisfy the inequality.

[12] Right-hand rule defines the direction of a positive cross product; given two perpendicular vectors, A and B, pointing the right index finger along a vector A and the right middle finger toward vector B ensures that the thumb finger points in the direction of the vector $A \times B$, where all vectors are perpendicular to each other.

[13] The dilation, for a given source (node S) and a destination (node D), is the ratio between path length selected by the FACE algorithm to the path length selected by a shortest-path algorithm. The average dilation is the average of the dilation ratio over all source–destination nodes in the network. Low average dilation means the traffic is routed via shorter paths.

[14] Sparse graph is a graph with only a few edges.

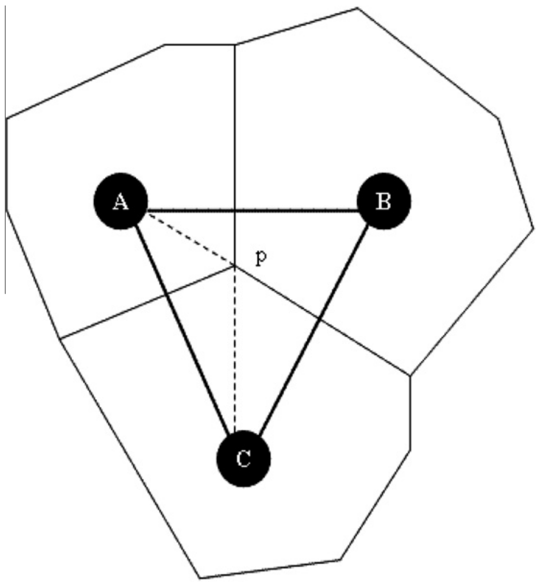

Fig. 14. Example of creating different Voronoi region in a given graph. To establish Voronoi regions, draw a perpendicular line at the middle of each graph edge that connects each node with its direct neighbors. These lines are the boundaries of the Voronoi region for each node. Point p is called the Voronoi vertex which is the point where the Voronoi regions intersect.

beacons) to update their information. This limits the control-message overhead to the direct neighbors only.

GPSR uses two forwarding schemes: GF and perimeter forwarding. GF is the primary scheme to forward a data packet from a source node to its destination node. When a packet reaches a dead end (when all neighbors of a node are farther away from the destination than itself, called GF empty-neighbor-set problem), perimeter forwarding, which is based on FACE routing technique, is performed as a backup. Perimeter forwarding first determines the planar graph using the RNG, as discussed earlier, and then the planar graph faces are traversed using the right-hand rule hop by hop along the perimeter of the region, as shown in Fig. 13.

During perimeter forwarding, whenever the packet reaches a location that is closer to the destination than the position where the previous GF of the packet had failed, the greedy process is resumed.

Perimeter forwarding is not a loop-free process; a loop can occur when the destination is not reachable. In the worst case, GPSR can possibly generate a very long path before a loop is detected but once a loop is detected, GPSR drops the packet.

GPSR is scalable and maintains mobility. GPSR requires exchanging a small amount of control messages, and GPSR works best for dense wireless networks. On the other hand, GPSR increases the path length which may increase packet drops.

NS-2 was used to compare GPSR and DSR [63] performance which can be found in [64]. In summary, GPSR offers higher packet delivery ratio and lower routing overhead than DSR. On the other hand, DSR performs better than GPSR when the number of hops along the path increases.

3.2.3. Geographic Routing without Location Information (GRLI)

GRLI [97] is a Geographical routing algorithm that can perform routing without the need for location information. In GRLI, there are three main rules followed to route a data packet; these rules are: Greedy, Stop (when a data packet arrives at its destination), and Dead-end (when a data packet cannot perform greedy progress, i.e., 'GF empty-neighbor-set' problem occurs). GRLI performs an extended ring search[15] when a GF empty-neighbor-set problem occurs while executing the GF process. This search continues until a closer node is found on the direction towards the destination. If the search fails, the ring search is extended until a predetermined Time-To-Live (TTL) counter expired.

In GRLI, a node uses the virtual coordinates which are related to the node itself, the node's direct neighbors, and the neighbors of the direct neighbors. These virtual coordinates are not initially known by the nodes, but each node learns these virtual coordinates by running the coordinate assignment algorithm. The coordinate assignment algorithm works as follows: two nodes in the network are predetermined to be the designated bootstrap nodes. The bootstrap nodes select another type of nodes which are called the perimeter nodes. Each perimeter node broadcast its coordinates to the entire network to allow every other node to calculate the node's perimeter vector, which includes the distance from that node to all perimeter nodes. Then, each bootstrap node and each perimeter node broadcast their perimeter vectors to the entire network. Now, each node can compute normalized coordinates for itself and for the perimeter nodes by comparing the node's perimeter vector and the received inter-perimeter vectors from the bootstrap nodes and the perimeter nodes.

GRLI is scalable, with respect to network size, and outperforms GF when the network suffers from unfavorable wireless conditions (e.g., when a large number of obstacles exist).

3.2.4. Bounded Voronoi Greedy Forwarding (BVGF)

BVGF [120] is a geographical localized routing algorithm. Similar to GF, in BVGF, the greedy routing decision is made based on the location of the direct neighbors of each node. However, only a subset of the direct neighbors is considered to handle the forwarding process. This subset, which is called the eligible set of neighbors, consists of neighbors whose Voronoi regions are intersected by the line joining the source and the destination. Fig. 14 shows the creation process of the Voronoi region for each node in the graph. Each node selects the next-hop node based on the following:

[15] From [37]: "Given any destination node (x_d,y_d) and any other source node (x_s,y_s), an immediate neighbor of (x_s,y_s) exists, (x_i,y_i), which is closer to (x_d,y_d). Within one hop of any node must be a neighbor closer to the destination. The progress is to forward through any path from (x_s,y_s), of hop-count less than or equal to n, to a node (x_i,y_i), for which the distance $[(x_i,y_i)$ to $(x_d,y_d)]$ is less than the distance $[(x_s,y_s)$ to $(x_d,y_d)]$. When some node is reached for which no immediate neighbor is closer to the destination, a search of no farther than $(n-1)$ hops finds a node that has a neighbor that makes progress. Successive reapplication yields a path between source and destination. It is intuitively clear that any route composed of segments, each of which makes progress, cannot form a loop."

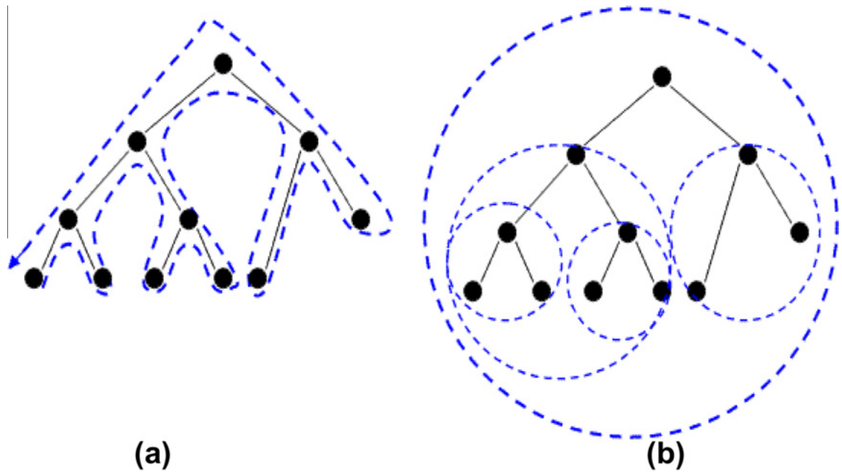

Fig. 15. Examples of (a) a spanning tree and (b) a hull tree [74].

- has its Voronoi region intersect with the source–destination line segment, and
- has the shortest Euclidean distance to the destination among all eligible neighbors.

BVGF can find a short routing path compared to GF. This has been tested by a C++ coded simulator in [120]. In average cases, both GF and BVGF perform similarly. However, BVGF has a lower Euclidean dilation, which is useful for real-time communication protocols that are sensitive to the end-to-end communication delay.

3.2.5. Greedy Distributed Spanning Tree Routing (GDSTR)

Unlike other geographical routing algorithms, GDSTR [74] does not use the face planarity as a recovery method from GF. When GDSTR needs to forward a data packet, GDSTR starts with GF. If GF empty-neighbor-set problem occurs, GDSTR switches to forwarding based on a hull tree. In this case, the convex hulls[16] are used to decide the forwarding direction towards the destination. Then, GDSTR returns to GF whenever it is possible to do so (when GF neighbor's set is not empty).

A hull tree, which is the technique used by GDSTR to recover from GF, is a spanning tree, as shown in Fig. 15, where each node is associated with a convex hull. The convex hull contains the locations of all its descendant nodes in the tree. When a packet reaches a local minimum,[17] different approaches are followed to forward the packet, based on the status[18] of the destination node.

[16] From [74]: "the convex hull for a set of points is the minimal convex polygon that contains all the points; the convex hull is minimal because the convex hull is contained in any convex polygon that contains the given points. The hull is represented as a set of points (its vertices), and this set could be arbitrarily large."

[17] A local minimum, in GDSTR, is a node that has no other nodes attached to it and have higher level than the local minimum. In other words, the local minimum is the leaf node of the tree.

[18] The destination status can be one of the following: (1) the destination is not located within a convex hull of any of the child nodes and (2) the destination is located within a convex hull of at least one child node.

GDSTR, compared to the planar-based algorithm such as GPSR [64], requires less maintenance bandwidth (characterized by the average number of messages that each node in the network would have sent or forwarded before the network stabilizes), and routes packets along shorter paths than GPSR. However, in GDSTR, nodes need to store all convex-hull information. Group high-level event-driven simulator was used to compare GDSTR with GPSR [74].

3.3. Flat addressing and widely-distributed information

In a wireless network, the distribution of mobile nodes over the network area and the limitation of each node's wireless coverage may cause a lack of information at some nodes about the structure of the network to which the nodes belong. Information-gathering process is an important phase of any routing approach. Therefore, a structural overview of a wireless network is significant to facilitate the routing process. In addition, a structured addressing scheme is needed to achieve the same goal and enhance the network performance. Hence, in this subsection, we discuss routing algorithms that propose new techniques to provide a structural addressing scheme or structural references which have the updated information of several nodes in the network.

3.3.1. Grid Location Service (GLS)

GLS [76] is a geographical routing technique which provides location service to speed up the routing process. The main idea of GLS is related to Distributed Location Servers (DLS), an idea which avoids bottleneck nodes. Using only the node ID, GLS can maintain the node's location on which each node frequently updates its location information in its predetermined Location Server (LS) nodes. The LS nodes form a small subset of nodes that are selected by a node from the total number of nodes in the network. When a source node needs to send a data packet to a destination node, the destination's LS nodes are the references which a source node needs to consult. The method of finding

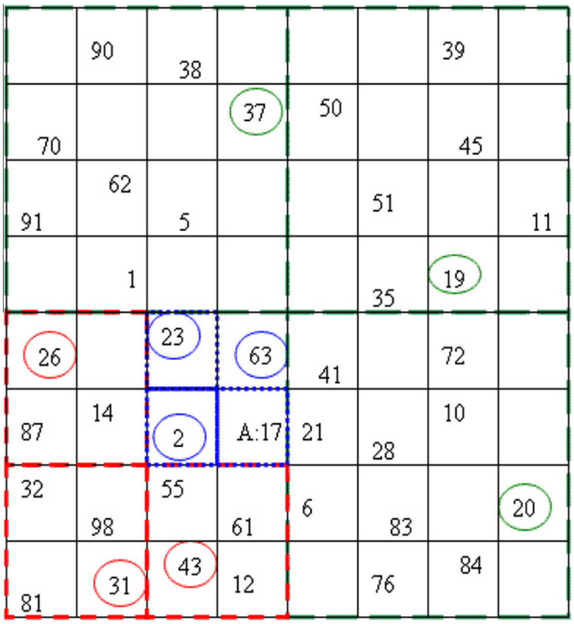

Fig. 16. Example (GLS): the number in each square represents the node ID; the location servers of node A are the nodes that have circles around their node IDs.

the destination's LS nodes is the same as the method that the destination node uses to recruit its own LS nodes.

Fig. 16 illustrates an example of how node A selects its LS nodes in a given network. Generally, the grid hierarchy consists of four squares in each level recursively, where the higher level is represented by the total area of the network that is divided into four subareas or squares in each lower level. Node A selects three LS nodes from each hierarchical level. The selection is based on the node's ID only where node A chooses the node that has the closest ID to its own ID to be one of A's LS nodes. GLS defines the closest node as the node with the least ID greater that A's ID; this ID space is a circular one which functions like the "mod" function that is based on the ID of node A. For instance, node A (with ID equals to 17) selects nodes (2, 23, 63) at level 1, nodes (26, 31, 43) at level 2, and nodes (19, 20, 37) at level 3, to represent node A's LS nodes.

GLS is scalable, tolerant to node failure, and works better when the network is dense. On the other hand, GLS increases overhead, increases the number of steps to reach the destination, and has a more complex procedure relative to the other Geographical RAs; additionally, according to the way of selecting the location server in GLS, a node knows the location information of all the other nodes in the network, not only its neighbors, which means GLS has practical concerns. All these aspects increase the complexity of the algorithm.

3.3.2. GPS Ant-Like Routing Algorithm (GPSAL)

GPSAL [19] is a geographical routing algorithm that uses GPS to provide the location of each node which may reduce the number of routing messages. Similar to GLS, GPSAL limits the number of nodes that each node needs to update with the latest location information. In GPSAL, the updated nodes are called Ants because these nodes run the Ants program. Ants are mobile software agents used to maintain more up-to-date global location information of the non-neighboring nodes. The main job of Ants is to collect and distribute the node's location information around the network. During the routing process, the intermediate nodes can use the routing information carried by the forwarded message to update their routing tables.

Ants can speed up the routing process because Ants accelerate the process of updating the routing information. However, this also increases the network overhead. Hence, the number of Ants in the network should be controlled.

Generally, GPSAL matches the nature of the fixed Infrastructure network, such as WMN, because, based on the results in [19], the cost to route packets in a fixed Infrastructure is much less than that in a mobile network. GPSAL emphasizes the way of updating the routing tables, locally (among neighbor nodes) and globally (at any node in the network).

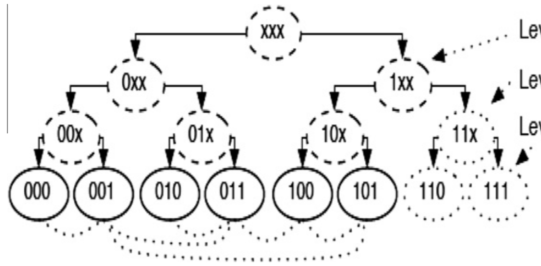

Fig. 17. DART example from [35].

3.3.3. Dynamic Address Routing (DART)

DART [35] is a hierarchical routing algorithm aimed at developing a scalable routing protocol for mobile Ad-Hoc and mesh networks. DART achieves this goal by efficiently implementing a dynamic addressing mechanism which can assure scalable routing in large wireless networks. Because of the large number of end-user nodes, routing in large networks becomes challenging. Hence, in an Ad-Hoc network, a scalable solution for routing is needed.

DART addresses the scalability problem from the addressing scheme prospective. Therefore, instead of using the flat addressing method, DART implicitly includes the node's location information within the node's address by splitting the address of a node into two separate parts:

(i) a static but unique node identifier, which is equivalent to the current IP addresses, and
(ii) a dynamic routing address, which is related to the current node's location in the network topology. The use of dynamic routing addresses allows route aggregation that can support scalability in DART (see Fig. 17).

Fig. 17 shows the address tree of a 3-bit binary address space. The actual addresses are captured by the leaf nodes. The intermediate tree nodes show the common addresses of a group of nodes. The dotted lines in Fig. 17, which connect the leaf nodes, are the actual physical link addresses.

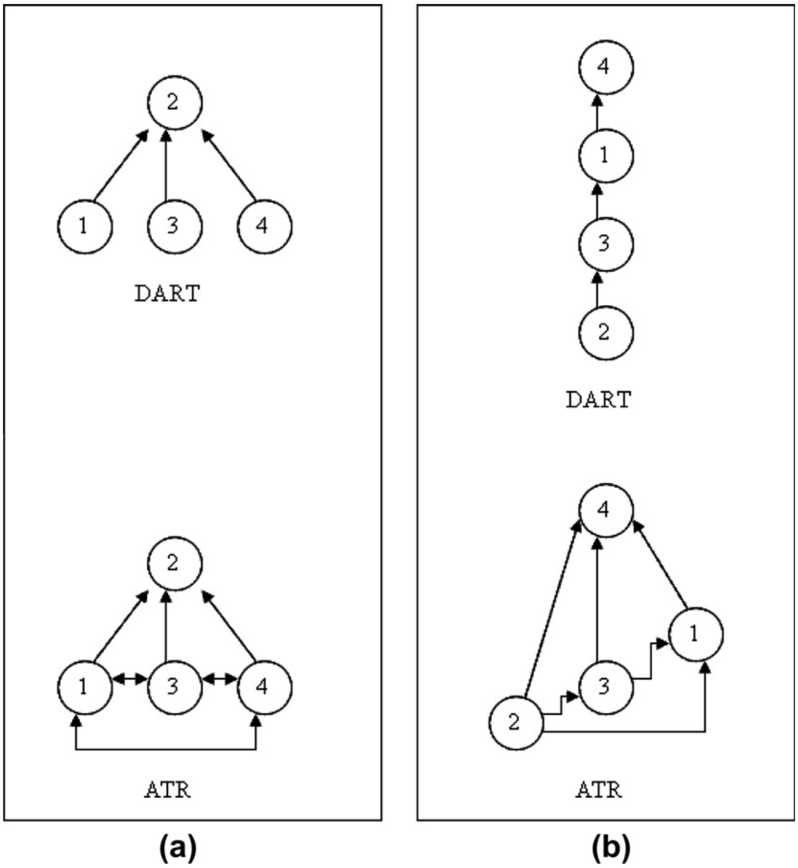

Fig. 18. ATR [18]: graphs referring to path discovery process: (a) node 2 is the final destination and (b) node 4 is the final destination.

Because DART is an addressing-based technique, DART is compatible with a heterogenous network that supports different types of links, such as wireless omnidirectional links, directional links, and wired links. In addition, DART is compatible with the application of both Wireless Mesh Network and Ad-Hoc network.

3.3.4. Augmented Tree-based Routing (ATR)

ATR [18] is a multi-path hierarchical routing algorithm that is based on a structured address space. Like DART, ATR proposes a scalable routing solution for wireless networks. ATR enhances the DART procedure by adding the multi-path feature to DART. Hence, in ATR, redundant paths are established from any intermediate node towards the destination node to increase the flexibility and reliability of a network. However, using the augmented tree structure[19] in ATR increases the path cost.

In Fig. 18, both DART's and ATR's route-discovery schemes are shown. In this example, a fully-connected four-node graph is used to show the differences between the selected number of paths by DART and ATR.

[19] An augmented tree uses a simple ordered binary tree which is used mainly for search [11]. The augmented tree-based protocol exploits a distribute hash table (DHT) system [18].

3.4. Large power consumption

In a multi-hop Ad-Hoc network, the existence of any intermediate node depends on its battery power; once the battery of a node is drained out, then the routing process should reroute the traffic which used to pass through this node. Hence, minimizing the power consumption of a node is important to stabilize the network and reduce its cost.

In this subsection, we discuss some of the power-aware routing algorithms and describe their different methods to efficiently save the network power.

3.4.1. Infra-Structure AODV for Infrastructured Ad-Hoc networks (ISAIAH)

ISAIAH [78] is an Ad-Hoc power-aware routing algorithm. The forwarding approach of ISAIAH is similar to AODV routing protocol. The difference between ISAIAH and AODV is that ISAIAH selects routes that pass through Power Base Stations (PBSs) instead of through mobile nodes. This can save the amount of power that might be spent by these mobile nodes. However, the path selected by ISAIAH can be longer than the path selected by AODV. Additionally, ISAIAH allows nodes to enter a power-saving mode for a short period of time which significantly reduces the power consumption compared to AODV.

3.4.2. Power-Aware Multi-Access Protocol with Signaling Ad-Hoc Networks (PAMAS)

PAMAS [102] is an Ad-Hoc power-aware routing protocol that controls the battery usage based on the frequency of a node's activities. PAMAS manages the distribution of power at the network nodes to compromise between network connectivity and power consumption. This is achieved by powering off nodes that are not participating in the process of transmitting or receiving data packets for a certain amount of time. It has been shown in [102] that PAMAS, by powering off nodes, does not affect the network performance.

3.4.3. Dynamic Source Routing Power-Aware (DSRPA)

DSRPA [29] is another power-aware routing protocol. Similar to PAMAS, DSRPA trades off between network connectivity and power consumption by defining a new routing metric. In DSRPA, battery freshness is considered in routing to achieve connectivity for the longest period of time. Hence, nodes with freshest battery are selected to route data packets around the network.

3.4.4. Power-Aware Routing Optimization Protocol (PARO)

PARO [46] is a power-aware routing algorithm that aims to increase the path length to reduce the total transmission power. In PARO, new forwarding nodes (called 'redirectors') are added on the routing path to reduce the transmission power of the intermediate nodes along the original path. In other words, PARO attempts to reduce the individual hop's distance to reduce the overall power consumption. The traditional method of transmitting data in a wireless network is to use the maximum transmission power to decrease the number of hops along the path. Routing protocols such as AODV [92], DSR [63], and TORA [90] are based on the traditional routing methods which minimize the number of hops along the path. Unlike these routing protocols, PARO scarifies the path length to conserve power.

3.5. Interference and load balancing

Routing in a wireless network is challenging due to the unpredictable behavior of the wireless shared medium and due to the effect of interference on wireless link capacities. Interference is a major factor that limits the performance of wireless networks and is difficult to control in a wireless network. Thus, the impact of interference on link capacities should be considered in a wireless routing algorithm.

Interference impacts both the sender and the receiver of a wireless link. At the sender side, the sending rate will be reduced by the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA)-based Medium-Access Control (MAC) layer interaction. At the receiver side, interference causes collisions.

In the literature, a number of interference-aware routing solutions were proposed, such as Expected Transmission Count (ETX) [27], Expected Transmission Time (ETT) [31], Weighted Cumulative Expected Transmission Time (WCETT) [31], A Location-Aware Routing Metric (ALARM) [7], Metric of interference and Channel-switching (MIC) [121], and others. These solutions are cross-layer routing metrics that consider the underlying physical interference from which a wireless link could suffer. The interference-aware routing metrics can be implemented using any given routing algorithm, based on the metric's compatibility with the provided routing algorithm. But there are also some routing algorithms which have been developed based on the interference-aware feature.

Load balancing is not a new issue and is not restricted to wireless networks only. This term is not new and has been studied by researchers for wired and wireless networks. In a network, due to resource sharing, it is possible to have a congested (or bottleneck) link. A load-balancing routing solution should avoid the congested routes, especially for the newly-arrived traffic flows. In load-balanced routing, the bottleneck links should be excluded from newly-selected route.

In a typical network, the performance metric Round-Trip Time (RTT) is used to achieve load balancing. But, in a wireless network, RTT is not always enough to balance the load because of the dynamic characteristics of the wireless environment.

In a wireless network, interference and load balancing are related to each other. Any routing solution considers load balancing should also consider interference. To balance the load of traffic flows, routing should be aware of the physical wireless interference; then, routing can build up a load-balancing solution to shift a traffic flow from a bottleneck link to a lightly-loaded link. On the other hand, a routing solution that considers interference eventually achieves a load-balancing network because the link that suffers from high interference causes congestion, and by avoiding high-interference links, traffic flows are routed through low-interference links, which is a load-balancing routing solution. Therefore, in this section, we discuss the routing algorithms that consider both interference and load balancing.

3.5.1. Source Routing for Roofnet (SrcRR)

SrcRR [5] is a routing algorithm that is implemented by the Roofnet testbed [22]. SrcRR's main idea is to utilize high-throughput routes during the routing process. SrcRR considers the wireless environment challenges, such as the interference that causes unstable link quality and frequent packet loss.

The design of SrcRR is generally inspired by DSR [63]. Source routing gives the source more flexibility over how soon it switches to a new route. SrcRR is independent of IP layer, and operates at a lower layer.

In source routing, when a node (node S) needs to find a route to a destination (node D), node S broadcasts a query packet to node D. Each intermediate node (node i) appends its own identifier (ID) to the source route of the received packet and forwards the query packet. Each time node D receives a query sent to itself, node D sends a reply back to node S along the same source route found by the query packet. On the way back of the reply packet (ACK), Node S and every intermediate node store the links' information mentioned in the ACK. Node S applies a shortest-path routing algorithm to find the best route from itself to node D. When node S sends data packets to node D, it includes route information (i.e., the sequence of nodes' IDs along the route) in each data packet as a source route.

SrcRR differs from DSR by replacing the hop-count routing metric with the Expected Transmission Counts (ETX) [27] routing metric. ETX is an interference-aware link-based routing metric that continuously measures the link loss rate in both directions between each node and its direct neighbors using periodic broadcasts.

In ETX, the link cost is an estimation of the number of transmission attempts, including retransmissions, based on the link's physical characteristics. Because ETX is a link-based routing metric, the path cost is the sum of the link ETX metrics along this path. Therefore, ETX assigns high cost to long routes and routes with high-loss-rate links.

3.5.2. Link Quality Source Routing (LQSR)

LQSR [30] is based on the basic DSR functionalities, such as the route-discovery process and route-maintenance process. LQSR is also considered as a link-state routing protocol because, in LQSR, a link information is cached instead of a route information.

Unlike DSR, the implementation of LQSR is done at Layer 2.5 instead of Layer 3. The asymmetric link-quality metric is used as a link cost in LQSR.

Each LQSR node occasionally sends a link information message. The link information carries the recent link metrics for all the links that lie along the route from the originating node to the received node (any node receives this link information message). Because the link information is piggy-backed on a route request, link information floods fast throughout the neighborhood of the node.

Microsoft uses LQSR in its Mesh Network solution. In Multi-Radio (MR) systems, MR-LQSR replaces the link-quality routing metric with the Weighted Cumulative Expected Transmission Time (WCETT) [31] routing metric. WCETT is a route-based interference-aware routing metric that considers the heavily-loaded links in the network and assigns them higher costs. The solution of WCETT is proposed for multi-radio/multi-channel wireless networks. WCETT is composed of two main parts: the sum of all links' costs (ETTs) along the path, and bottleneck channel which has the maximum sum of ETT. WCETT considers the intra-flow interference (interference between nodes on the same path) but not the inter-flow interference (interference between nodes on different paths).

3.5.3. Load-Balancing Routing for Mesh Networks (LBRMN)

LBRMN [121,122] is an interference-aware load-balancing routing algorithm that is used for multi-radio/multi-channel wireless mesh networks (WMN). LBRMN's main solution is based on a routing metric that is called Metric of interference and Channel-switching (MIC). In MIC, the first requirement of good wireless-routing metric should consider both intra-flow interference and inter-flow interference. The second requirement of a good wireless-routing metric is to be isotonic[20] [105]. The isotonicity property ensures the efficiency of the routing algorithm.

[20] From [121]: "A weight function $W(\cdot)$ is isotonic if $W(a) \leqslant W(b)$ implies both $W(a \oplus c) \leqslant W(b \oplus c)$ and $W(\acute{c} \oplus a) \leqslant W(\acute{c} \oplus b)$ for all paths a, b, c, $\acute{c}$, where operator $\oplus$ represents the concatenation of two paths."

MIC is composed of two main parts: Interference-aware Resource Usage (IRU) and Channel-Switching Cost (CSC). IRU and CSC capture the effects of inter-flow interference and intra-flow interference, respectively. To achieve isotonicity, the real network is converted to a virtual network which has MIC as an isotonic link weight.

In LBRMN, MIC can be implemented in a link-state routing algorithm or a distance-vector routing algorithm with some modification to the routing table entry. In LBRMN routing table, three entries are needed: the destination address, the address of the next-hop node, and the channel that is used during the transmission to the next-hop node.

LBRMN requires additional routing tables for each radio interface of each node. Additionally, mapping the real network to a virtual network may cause complications during the implementation process.

3.5.4. Interference-Aware Load-Balancing Routing (IALBR)

IALBR [36] is a an interference-aware and load-balancing routing scheme that is based on AODV [92].

In IALBR, the routing metric (called load value) is not only the load at the node itself but also the load at the next-hop node. The next-hop load is estimated by the busy status of the channel that connects the node with its next-hop node. The load value sum of traffic is stored in the routing table to help find the lowest-load routes between the network's nodes.

The routing process starts with a route-discovery phase where the source node (node S) floods a Route Request (RREQ) message to discover a route to the destination node (node D). Only load values are used in the RREQ messages. At the intermediate node (node i), the received RREQ message is reviewed by node i. Node i creates a new routing table entry if the pair of source–destination entry does not exist in the table. This new entry includes a newly-built load value and a recorded previous hop to this entry. If the source–destination pair is a valid entry in node i's routing table, node i compares the load value that node i stored and the load value received in the RREQ message. Then, node i decides either to drop the RREQ or to update node i's routing table. At the destination side, node D verifies that the RREQ is sent to itself; then, Route Reply (RREP) is sent back to node S following the same source route that RREQ used before.

IALBR is not similar to AODV because, in addition to using a different routing metric, the intermediate nodes in IALBR do not pass back the RREP messages to the source node but each intermediate node collects the total load value of the traffic load. Hence, IALBR does not calculate the shortest-path route, but IALBR calculates the lowest-load route between any source node and its destination node.

3.5.5. Load-Balancing Curveball Routing (LBCR)

LBCR [94] is a geographical routing algorithm which is based on a modified routing metric implemented on a greedy routing scheme. The modified routing metric is obtained by projecting all nodes from a 2-D planar disc area into a 3-D sphere. The nodes' projection changes the real coordinates of each node to virtual coordinates which are used to develop the new routing metric.

The main idea of routing using the sphere is to avoid routing through the center of the sphere, which could be a hot spot or a congested point. Routes go greedily through the circles of the sphere which are called rings. Each node on the sphere is represented by the node's virtual coordinates which are used to create the new routes. The authors of this work implemented the idea of ring highways on wireless routing to balance the traffic load.

In LBCR, a recovery mechanism is used when the routing on the virtual coordinates fails; this mechanism is simply to fall back to the original 2-D greedy routing. When the first recovery mechanism fails, another backup recovery routing is performed by using any existing routing technique, such as GPSR [64].

The method of load balancing used in LBCR is as follows. The load of each node is monitored by all neighbor nodes. At each node, if the load of the next-hop node is higher than a predetermined threshold, which is relative to the node's own load, the node avoids that next-hop node by trying to route through an alternate neighbor. If a suitable neighbor is not found in 3-D coordinates, the node switches to one of the available routing recovery schemes.

LBCR is a reactive scheme, and it is simple to implement where only the neighborhood information is required. In addition, LBCR is considered as a good practical routing algorithm. On the other hand, there are some mapping limitation (from 2-D to 3-D), such as the mapping is not uniform (which could cause a sparse or disconnected network), the sphere is not completely covered (there are some parts of the sphere, like the top or bottom parts of the sphere, which have no node mapped to them), and the mapping parameters (such as power and sphere radius) are dependent on the network topology.

4. Summary and discussion

By exploiting the wireless network technology's advantages over the wired network, many researchers are engaged to develop a better solution for the different wireless networking aspects. Routing is an important process that has attracted researchers to enhance the performance of wireless networking solutions.

In this survey, we first focused on the variety of routing algorithms that are proposed widely in the literature. These routing algorithms, which are especially designed for wireless networks, were classified based on the characteristics of wireless networks into different categories such as Geographical, Geo-casting, Hierarchical, Multi-path, Power-aware, and Hybrid routing algorithms. This survey offered an intensive study of these categories of routing algorithms. In addition, this survey compared, analyzed, and discussed the relationships among the different categories and the routing issues that some of these algorithms try to solve.

Second, we discussed some practical issues that could degrade the performance of a wireless network such as large area of flooding, GF empty-neighbor set, flat addressing, widely-distributed information, high power consumption, interference, and load balancing. For each problem, we described the routing algorithms which offered solutions to overcome these issues based on different routing techniques. Each of these routing algorithms is originally categorized under one or more of the routing algorithm categories which were discussed in Section 2.

In the following subsections, we conclude our study of the routing-algorithm categories and the wireless routing-algorithm issues which were discussed in Sections 2 and 3, respectively.

4.1. Routing-algorithm categories

Multiple categories of routing algorithms can share some common properties. As a result, several routing algorithms can be placed into multiple categories. For instance, the Zone-based Hierarchical Link State (ZHLS) [62] is listed under two different categories: Geographical as well as Hybrid. All of these routing algorithms can also be classified under centalized/distributed and proactive/reactive classes.

The overlap between RA categories is relevant to each category's different characteristics. For instance, a routing algorithm can be Hierarchical and use Hybrid routing criteria. Another algorithm might use location information (Geographical RA) to deliver messages from a source to its destination via a Multi-path routing approach. These examples are possible because each RA category represents one feature of the routing algorithm. However, having different RA categories simplify the process of developing a routing algorithm based on the given environmental requirements. Therefore, we believe that the diversity in RA categories allows researchers to implement a precise solution for routing in wireless networks.

The wireless environment defines the challenges that the design of a wireless network should adapt. Routing is one of the design issues that should be considered in wireless networks. Based on the wireless environment challenges, one routing-algorithm category can match the nature of the given wireless network more than the other categories. Therefore, the major task of a wireless-network administrator is to study the available routing-algorithm categories and select the perfect match to the given wireless network. Hence, in this survey, we studied the routing-algorithm categories that are provided in the recent literature.

4.2. Wireless routing-algorithm issues

In Section 3, we discussed different routing algorithms which differ on their purposes and techniques to capture the properties of the wireless environment. Therefore, based on the network characteristics, the matching routing algorithm can be selected. For instance, if scalability has priority in a network with high density of nodes, then GLS or DART is a good choice. On the other hand, if the objective is to have a fault-tolerant network, then TORA or ATR can be considered as a routing solution because both algorithms support multiple routing paths. As a variation of TORA, GeoTORA (with its multi-casting capability) can be used when multi-casting is needed. Similarly, LBM and GeoGRID are the multi-casting variations of LAR. In addition, for power saving, PAMAS considers a node's activities to power off the least-active nodes. Hence, choosing a routing algorithm is not unique, but the choice has to match the network characteristics for which the algorithm will be used.

In some cases, we found similarities and differences between the routing algorithms to serve the same purpose. As an example, DREAM is similar to LAR from a structural point of view (i.e., both algorithms reduce the area from which the sender can select the next hop). This will limit the area of forwarding and eliminate some of the nodes that are neighbors but not within the selected area. The differences between DREAM and LAR mainly lie on the concept or definition of such an area. Thus, DREAM does routing which strongly depends on the speed of mobility of each node which matches the Ad-Hoc network but not the WMN.

When the complexity of a routing algorithm is not an issue, an advanced routing algorithm can be used which could be an enhanced version of other routing algorithm. For instance, FACE routing technique is utilized as a first step in GPSR which is more complex than FACE.

In addition to satisfying the network priorities, the simplicity of an applied routing algorithm is an important property to consider while selecting the proper routing algorithm.

In this survey, we focused our discussion on the routing algorithms described in Section 3. There are several other ideas published under different routing-algorithm categories such as ExOR [13], XoRs [66], MiSer [95], EWI [65], EGR [71], etc. Each of these routing algorithms considers an important issue in wireless routing, which go beyond the categories surveyed in this paper. For instance, References [13,66,65] proposed novel approaches related to routing in Ad-Hoc networks. Reference [95] proposed an efficient routing technique that reduces the overall power consumption while routing in wireless networks. Finally, Reference [71] provided a practical routing algorithm that considered special wireless issues.

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