

Surveying Position Based Routing Protocols for Wireless Sensor and Ad-hoc Networks

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Abstract: A focus of the scientific community is to design network oriented position-based routing protocols and this has resulted in a very high number of algorithms, different in approach and performance and each suited only to particular applications. However, though numerous, very few position-based algorithms have actually been adopted for commercial purposes. This article is a survey of almost 50 position-based routing protocols and it comes as an aid in the implementation of this type of routing in various applications which may need to consider the advantages and pitfalls of position-based routing. An emphasis is made on geographic routing, whose notion is clarified as a more restrictive and more efficient type of position-based routing. The protocols are therefore divided into geographic and non-geographic routing protocols and each is characterized according to a number of network design issues and presented in a comparative manner from multiple points of view. The main requirements of current general applications are also studied and, depending on these, the survey proposes a number of protocols for use in particular application areas. This aims to help both researchers and potential users assess and choose the protocol best suited to their interest.

Keywords: survey, position-based routing protocols, geographic routing, wireless sensor networks, ad-hoc networks, applications

1. Introduction

Recent advances in wireless and mobile electronic communication technology has led to increased attention to wireless ad-hoc and sensor networks. Numerous position-based routing algorithms have been proposed to satisfy the demands of particular networks and real applications. According to the considered type of network, the protocols present certain characteristics recommending them more or less for certain applications in various areas. This article surveys and compares a vast number of such protocols (almost 50) and considers geographic routing as a particular type of position-based routing with many advantages worth considering. Based on the analyzed protocol characteristics, the survey also makes suggestions of application suitability based on the requirements of the application areas.

Position-based protocols are currently being thoroughly studied due to their application potential in networks with demanding requirements. Their main characteristic is that they make use of location information for routing decisions. From all the position-based protocols, the geographic approach is the one which captures the attention mostly due to its numerous advantages, as stated in Section 3, in a discussion made on geographic versus non-geographic routing, in the context of location aided routing. Geographic routing is an elegant way to forward packets from source to destination in very demanding

environments without wasting network resources or creating any impediment in the network design. Therefore it is generally considered as an attractive routing method for both mobile wireless ad-hoc and sensor networks (ad-hoc and sensor networks). However, as all location based algorithms, it does not completely lack from drawbacks because it is based on localization, an intrinsic source of communication errors (aspect elaborated in Section 2).

Geographic routing represents the algorithmic process of determining the paths on which to send traffic in a network, using position information/geographic location only about source, neighbours and destination. It is considered substantially better from an energetic point of view due to the use of solely local information in the routing process. As a result of very little routing information being needed, no energy is spent on route discovery, queries or replies, node memory requirements are decreased and traffic overhead and computation time are considerably reduced. Also, in this sense it is different from source routing in which the sender makes some or all the routing decisions by having mapped the network and specifying in the packet header the hops that the message has to go through. In geographic routing, the process is localized and distributed so that all nodes involved in the routing process contribute to making routing decisions by using localization methods and computing the best forwarding options.

The clear benefits of geographic protocols are not offered by all position-based routing protocols. Some position-based protocols make use of different types of routing which create unnecessary overhead and consume extra energy, unlike pure geographic routing. Their approaches sometimes clearly belong to a specific routing category, such as reactive and proactive routing or represent a hybrid. However, each protocol has its strengths and weaknesses and all of the position-based protocols present a novel idea or improve an old one. It is only fair to say that some of the non-geographic methods can be more attractive for specific network environments and scenarios.

Position-based routing altogether can be used for a very high number of applications in a number of areas such as industry, home, health, environmental, military, automotive and commerce. From monitoring and control of industrial equipment, to emergency situation surveillance and physical world surveillance, any application needs a network design with robust routing, with a high expectation of packet delivery, successful route discovery even in mobile scenarios and capability to maintain connectivity for as long as possible without

manual intervention. However, not all position-based protocols perform well from all points of view (as seen in Section 5).

The goals of the applications presented in this article reveal particular routing requirements which can be successfully fulfilled by a number of protocols. However, the differences in these routing approaches make some protocols more recommendable than others. One must be able to choose the most suitable option from a vast number of geographic routing possibilities, but this poses a lot of difficulties. Therefore, this survey comes as an aid to those interested in position-based routing, and especially in geographic routing, and their implementation in commercial applications. It presents the existing routing protocols in a comparative manner and describes the possible requirements of each application area. Using this information, protocol suggestions are made for possible applications in each of these areas.

Numerous valuable routing taxonomies have been published prior to this paper [1-8], all contributing to a better understanding of forwarding mechanisms and their comparative performance. However, because the interest in network routing has resulted in a vast literature being developed, these papers have been more or less selective [4]. While some surveys are very detailed covering numerous algorithms, they do not take into consideration some novel protocols because of their date of publication [5] [7-10]. Some do not focus their study only on position-based routing and just use few algorithms as examples [2] [4] [6]. Others focus only on certain aspects, like mobility [10] or forwarding strategies and the local minima problem [11].

It is for these reasons this paper proposes a survey of position-based routing algorithms and protocols, with an emphasis on geographic routing, oriented on application suggestions for each studied protocol. Some of the contributions made by this survey are listed here:

- The work covers almost 50 protocols trying to offer a comprehensive view on the research conducted on position based routing algorithms, some of which belong to very recent literature
- A distinction is made differentiating geographic routing as a branch of positioned based routing. Other papers use the terms 'position-based' and 'geographic' in a generic way when referring to location aided routing and do not focus on geographic routing in particular considering the two synonymous [5] [8]. As a consequence the definition of geographic routing can be considered to coincide with that of position based routing. This survey defines geographic routing encompassing it within position-based routing. The distinction is used in the categorization of position based routing, bringing a novel factor in comparison with other more generic surveys.
- The survey provides application related analysis and suggestions. Prior literature also fails to provide specific details related to applications. While some authors make some application suggestions for their developed routing algorithm, others do not. Existing taxonomies are not developed in this direction either and even if they

do contain such information, like in [3], it is not well developed.

The rest of the paper is organized as follows: Section 2 presents the network types for which position-based routing can be used. Section 3 categorizes position-based routing and extends the motivation in Section 1 by characterizing position-based routing types and geographic routing in particular. Section 4 details the general routing design parameters used in the assessment of routing protocols. The comparison of the protocols is made in the appended tables. Section 5 briefly describes the functionality of the position-based routing protocols brought into discussion and makes reference to the attached tables for their comparison. Section 6 analyzes the demands of the areas in which position-based routing is applicable. Based on this analysis, an additional table suggests which of the routing protocols introduced in Section 5 would match the requirements of the applications in each area. Finally, section 7 concludes the paper with lessons learned and possible future work.

2. Network Types: Differences and Similarities

Position-based protocols are generally designed for either ad-hoc networks or sensor networks (static or mobile) because of the differences between the two network types. Leaving aside mobility issues which are challenging for both types of networks and comparing network demands, it can be stated that latterly developed position-based routing algorithms, if designed for static WSNs, can be used for static ad-hoc networks as well. However, WSNs are usually more demanding (as it will be revealed from the following paragraphs) and require better developed routing strategies.

Ad-hoc networks differ from WSNs through numerous aspects such as purpose, energy constraints, network life time, degree of mobility, scalability, device prices, node identification, cross-layer design, communication, fault tolerance and maintenance needs [6]. WSNs are designed for information collection, sometimes from remote areas where maintenance and sensor replacement is not possible [9]. Sensor networks consist of distributed autonomous sensor nodes which monitor physical or environmental conditions according to application demands and report the information to a single or to multiple sinks. Ad-hoc networks are designed for distributed computing and, in some cases, their resource saving requirements are not as demanding as the ones of WSNs, as it can be seen from the following paragraphs. WSNs' main concern refers to energy constraints, while ad-hoc networks, and especially MANETs, need to benefit from exact location information and to adapt to mobility. However, this does not imply that all WSNs are static or that they should not benefit from accurate node localization.

WSNs are often created for applications with numerous nodes (more than ad-hoc networks) and mobility requirements. Dynamicity results in additional energy expenditure, increased node failure and affected connectivity and network lifetime. In addition sensor nodes have reduced size and limited battery power. This leads to

increased power constraints for WSNs in comparison with ad-hoc networks.

The WSN size dictates sensor price i.e. economy of scale can be achieved. The degree of complexity of a sensor device should be minimal and any component which may increase node size or cost has to be carefully considered (such as GPS receivers) [3]. Also, because of the large number of nodes in mobile WSNs, the identification of nodes is no longer made through the hard wired unique MAC addresses as in the case of ad-hoc networks [4] [12]. In WSN end-to-end communication is preferred and the large amount of global identification overhead (tolerated in ad-hoc networks) has to be avoided. Instead of pre-wired identifiers, the nodes' identity is given by their location after deployment. The large amount of global identification overhead which can be tolerated in ad-hoc networks has to be avoided.

Other differences between WSNs and ad-hoc networks refer to layer and node communication. Because application level decisions may influence the design of all the layers, a cross-layer approach may be needed. Node communication sometimes differs for the two types of networks as well. WSN broadcast or multicast communication can replace the typical ad-hoc network unicast transmission.

However, though very different in purpose and level of demand on the routing component [3], [6] the two network types have important similarities: the unstable nature of their wireless communication, the lack of pre-deployed infrastructure, their mobile nature and ad-hoc deployment in some particular cases. WSNs can be dynamic when robots are used to carry the sensing equipment. Also, they can have an ad-hoc node placement when the distribution is not uniform, as in military applications. Therefore, even if the requirements for routing may seem different, both types can benefit from position-based routing. Because of scalability and energy efficiency issues, it is valid to consider that both WSNs and ad-hoc networks are suitable candidates for the implementation of a location based routing approach, as geographic routing.

3. Comparison of Routing Types

So far, there have been many routing algorithms proposed, but none offer the advantages of geographic routing. WSN routing algorithms have been classified by [3] as node centric, data centric, geo centric and QoS based [3] classifies them as destination initiated or source initiated, depending on the node where route setup is demanded and where the start-up point is. According to network architecture, routing algorithms can be categorized as implemented on a flat topology or a hierarchical one. In addition [7] mentions a classification which is regarded as optimal in this article's perspective: as topology-based and position-based algorithms. The paper also does not use this classification in the analysis of its selection.

A first amendment to the classification in [7] is that position-based routing should not be made synonymous with geographic routing whose definition is more restrictive. The work in [7] presents position based algorithms which make use of more location information

than just that of the source, destination and of the forwarding node (which contradicts the definition of geographic routing given in this survey). Such an example is the DREAM protocol which requires a position data base of all the nodes in the network. Furthermore, topology-based routing in [7] refers to proactive/table driven, reactive/on-demand and hybrid algorithms, which create routes ahead of events or on demand and memorize them at node level. Despite the fact that [7] is an overview of selected position-based routing protocols it also includes under this title topology-based routing algorithms such as SPAAR because it makes use of geographic coordinates. In this survey's view, it is considered more accurate to regard position-based algorithms as a general category of protocols which rely on location information and to categorize them into: topology-based and geographic routing. In addition, hierarchical position based routing is also discussed. Therefore, we shall use this categorization here and further explain the differences of these sub-types of routing.

Proactive (table driven or pre-computed) routing is achieved by creating lists or tables with destinations and possible paths towards the destinations. Periodically, these lists are distributed to nodes in the entire network, updating the link states. It makes use of broadcast techniques for the nodes' data updates and for route creation. Through this mechanism, proactive routing creates a lot of traffic, consumes excess bandwidth and a lot of power. Delays can also occur because of the slow network reaction to node mobility [6] [7].

Reactive routing (demand driven) can be a lower cost option than proactive because it does not use periodic broadcasts and initiates route discovery only when a message has to be sent, thus traffic decreases and overhead is reduced. However, using flooding and Route Request packets (blind broadcasts) does result in energy expenditure and high latency. Scalability issues and network clogging can appear because of flooding [6] [7].

Hybrid techniques of routing are designed to combine the advantages in both reactive and proactive routing, but in general their scalability can be a problem. They usually initiate routing through proactively determined routes and then certain nodes' demands are served according to reactive routing through flooding. The advantages depend on the application's traffic requirements [7].

Depending on the network architecture, i.e. on whether the nodes are homogenous or heterogeneous, routing algorithms can be classified as operating on a flat topology or a hierarchical topology. In a flat topology, all nodes are equal and are treated accordingly, while in a hierarchical topology, nodes are grouped on levels, and some nodes can become cluster heads having a different level of power. Geographic routing algorithms usually function on a flat topology, but they can be used in a hierarchical topology. However, some routing algorithms are purely hierarchical. In Hierarchical routing groups or clusters of nodes are created and data belonging to cluster members is combined to transmit it from one cluster level to another. This type of routing takes advantage of energy saving benefits like aggregation. Also, it scales well because nodes can join and leave a cluster any time as long as they are not designated cluster heads. They are

power efficient in finding routes, but they have excessive overhead due to the use of proactive and reactive routing. Proactive and reactive routing is used depending on the hierarchic level of the node.

So, non-geographic routing protocols display a considerable number of problems such as a high overhead due to bandwidth consumption and maintenance energy expenditure, low scalability problems and slow reaction to topological changes. On the other hand, geographic routing offers advantages resulting from the limited information needed at the node level. However it also suffers from an intrinsic problem that leads to inaccurate graph connectivity and persistent failures in both static and mobile networks.

Geographic routing can theoretically be performed based solely on location information of nodes, which can be obtained via the GNSS, where this is available, or via other location services. The source node has to be aware of its own position, the position of nodes within its range of communication (neighbour nodes) and of the destination. Therefore, the required node memory is minimal reducing bandwidth consumption and conserving energy. Nodes use broadcasting (on demand or periodically) to let their one hop neighbours know their location, but discovery floods and state propagation are not needed. So geographic routing results in minimal overhead. Also, because of the localized forwarding process, the network reacts faster, avoiding delays and overall latency [9][8].

Because geographic routing is based on knowledge of node coordinates, it relies on idealized assumptions about radios and their capacity to accurately serve node communication [12]. Two such impractical assumptions are the nodes' fixed radio range described by unit disk graphs (UDG) and the accurate location information they possess. The communication area of nodes is not predictable and proximity does not suffice. Obstacles may prevent nodes from being within range result in voids in the physical network topology and eventually in the failure of the forwarding strategy. Erroneous localization can degrade the routing performance in a number of ways: such as packets being dropped, non-optimal paths being selected, creating routing loops or affecting routing correctness [13]. In dynamic networks, localization of nodes is even more inaccurate. Distance measurements for nodes are inherently noisy and inaccurate as the nodes' transient location leads to inconsistent view of positioning information [13]. To avoid the manual programming of the location in all nodes within a network, as the means of obtaining the location information, sensor nodes can either be equipped with GPS or use a location discovery algorithm based on cellular networks or ranging techniques [14] for distance measurements. However, all localization methods have drawbacks: manual programming of nodes is sometimes difficult or impossible in remote areas or for large networks, the GPS increases device costs and power consumption and is less accurate indoors or where there is no direct line of sight between nodes and satellites, cellular networks require nodes to be in the range of the base station which is not always made possible, common range estimation methods like RSSI and TOF have other flaws: RSSI does not work well with increased distance and RF Time-of-Flight newly developed technology offers a restricted 1-2 m accuracy and requires sophisticated synchronization mechanisms [14]. As a

consequence, a number of papers have studied location errors and analyzed their effects on geographic routing and its applications [13], [15-20]. Solutions are being provided for practical implementation, but accurate positioning systems are still being investigated.

4. Routing Design Parameters

The performance of position-based routing algorithms can be judged according to the provision they offer for important design parameters. Problems may appear during routing such as packet cycling around the network without reaching their destination, packets being dropped and never being retransmitted due to node failure, package copies being transmitted in the network redundantly, consuming energy unnecessarily. Routing performance can be rated by the way protocols handle network challenges such as these. So, it is necessary to analyse the qualitative and quantitative routing characteristics of position-based protocols, as proposed by [21] and listed by [5] [7] [8], as well as other features which have not been given the same consideration. This is especially important when considering the implementation of a certain position-based routing protocol for a specific application. The following network characteristics are used for comparison purposes in the tables in Appendix 1 (entitled Protocol Comparison Tables). Because of space restrictions and of the amount of information encompassed, the comparison is made in multiple tables: Tables 2a-d use the first eight network characteristics, while Tables 2e and 2f use the last three. (For clarification purposes: Where the information is not available, the character '-' is inserted and where the protocols' characteristics depend on some other algorithm with which they are simulated or on factors which make them vary, the tables contain the wording 'depend'.)

1. Loop Free. Network information can be resent into the network to nodes that have previously received the same information. Thus sometimes data can circulate around the network on the same paths or between the same nodes which consider each other equally close to the destination. The result of such an event is the unnecessary consumption of network resources and packets failing to reach their destination. Proposed algorithms and protocols may or may not possess the quality of being loop free. Ideally this will occur without consuming energy and memory for maintaining information of past traffic and routes.

2. Distributed Operation. Networks can operate in a centralized, decentralized or distributed manner (Figure 1). Distributed algorithms can be classified as localized and non-localized. In localized algorithms, each node performs local computation and makes forwarding decisions using information related only to the position of itself, its neighbours and the destination. This is considered local behaviour with a global objective. Non-localized algorithms are either global, with each node knowing the positions of all the other nodes in the network and of their activity status, or zonal, nodes using localized algorithms within a certain perimeter, but using other routing mechanisms between zones [5]. Increased maintenance of routing tables at each node leads to the

characteristic that non-localized algorithms have overhead, additional energy expenditure and less scalability. This is why localized algorithms are preferred.

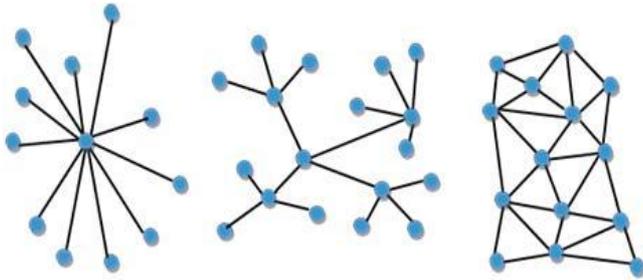


Figure 1. Network types of operation: Centralized, Decentralized, Distributed

3. Path Strategy. Algorithms can make use of certain methods of finding a path for packet transmission. They can use either the single path strategy which requires only a single copy of a packet is present in the network at any time, or the multipath strategy which requires a copy of the same packet to be sent on a few recognizable routes or on all possible routes (this last case is identified in packet forwarding as flooding) [5]. Combinations of the above mentioned strategies are also possible. However, the single path strategy is preferred for network resource conservation in an ideal localized algorithm [8].

4. Packet Forwarding. There are three main forwarding strategies which can be used: greedy [22-32], flooding [24] [33-37] and hierarchical [38]. Greedy forwarding is used when the message is able to advance from source towards the destination (Figure 2a). It does not imply route establishment or maintenance and the next hop. The decision is made according to the optimization criteria of the algorithm and does not guarantee that a packet reaches its destination [39]. Metrics can be hop count, geographic distance, progress to destination, direction, power, cost, delay, a combination of these, etc. [40-44]. If the message has reached a node which has no closer neighbours to the destination (a void or hole), a recovery procedure is necessary (Figure 2b) making the forwarding method a hybrid. Recovery from such a concave node can be done through flooding [25] [45-47] or perimeter (face) forwarding [39] [48-50].

Flooding is the forwarding strategy in which every incoming packet is sent through every outgoing link i.e. to all neighbours (Figure 3a). Restricted directional flooding (RDF in the tables) implies the packet is sent to all single hop neighbours towards the destination (Figure 3b). The neighbours which receive the packet check whether they satisfy the criteria to forward the packet or whether they should drop it. From these neighbours, several of them participate in the forwarding, not just one, to increase the robustness of the algorithm. This means that multiple copies of the same original packet are in the network at a certain moment in time. Directed/box flooding is used in the ALARM protocol [36] which floods the data packet in a rectangular area (box) oriented in the direction of the destination.

Hierarchic forwarding combines forwarding strategies according to hierarchical network structures (Figure 4). Some use zone based routing and some combine geographic routing with forwarding packets based on a proactive routing vector or on greedy strategies [7].

Recursive geographic forwarding (RGF in the tables) proposed by the GEAR algorithm [34] is a particular case of forwarding within a target region R where the packet is disseminated in an energy efficient way (Figure 5). The first node which receives the packet within R divides R into 4 sub-regions and forwards a copy of the packet to them. The splitting and forwarding continues recursively until there is one or no node per region left. When the minimal region R is empty the packet is dropped. The method is inefficient and sometimes does not terminate in low density networks.

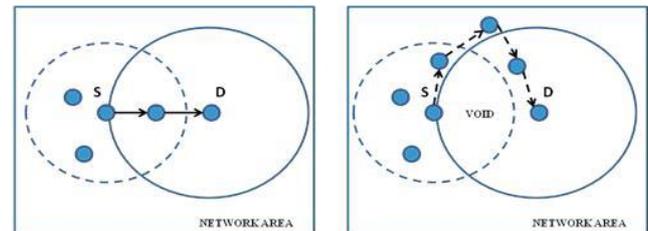


Figure 2. (a) Greedy Forwarding with Success
(b) Greedy Failure at node S

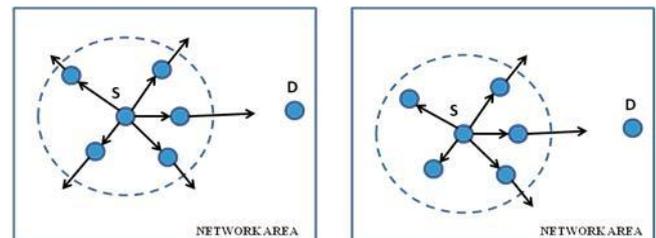
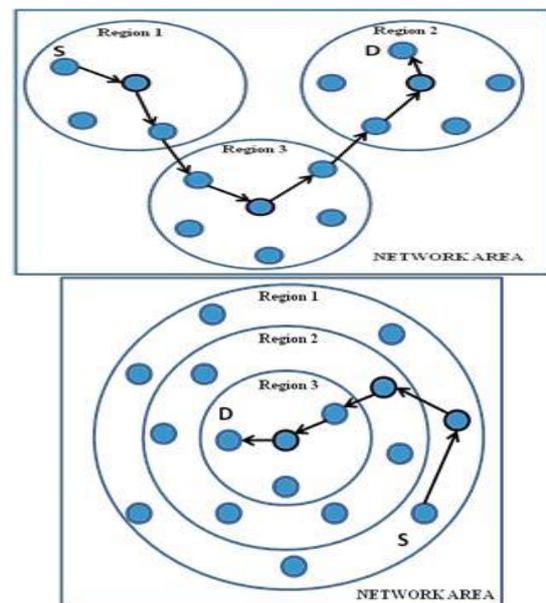


Figure 3. (a) Flooding
(b) Restricted Flooding



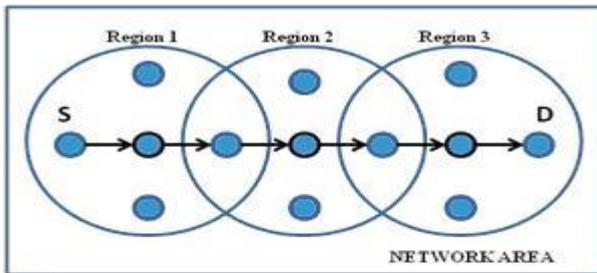


Figure 4. Examples of hierarchic networks with designated cluster heads

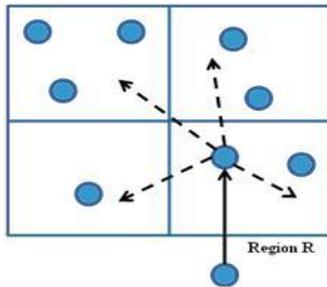


Figure 5. Recursive geographic routing

5. Path Selection Metric. Path Metrics are very important to routing algorithms because they reflect their goal and motivate a certain path selection. If there is a certain quality that the algorithm targets to attain, such as real-time routing or power efficient routing, this can be done through the optimization of certain metrics. The most common routing metrics are the hop count, the power metric and the cost metric [5]. Other metrics can be used as presented in [51].

6. Memory (state). As discussed earlier in this paper, there are routing algorithms which require nodes to maintain local or global information about the status of all the other nodes. Therefore, routing algorithms can be categorized according to the memory requirements of the nodes. If nodes need more than the position information of themselves, their neighbours and the destination, in this paper they are considered to have a memory requirement (statefull algorithms), even if the additional information is limited. Additional information may refer to the cost of the links to certain neighbours, the range of some nodes, node status, energy level, velocity, activity, cryptographic keys, destinations of nodes used in recent communication. Otherwise, the nodes are considered to be without memory requirement (stateless algorithm).

When mobility is involved, algorithms with additional memory requirements can have difficulties. Maintaining current accurate location information subject to topological changes causes high traffic, queues, congestion, overhead, latency and energy expenditure. Therefore it is desirable to avoid solutions which involve large memory demands at node level [5].

Note: Geographic routing, by definition, uses no memorization, so it is stateless. However, even if some protocols are categorized with memorization in the tables appended to this paper, they can be considered as belonging to the geographic routing category, because they do not store global information or routes to destination. Position-based protocols on the other hand

represent a larger sphere, which includes geographic routing, and they do make use of more node memory.

7. Guaranteed message delivery. The main purpose of a wireless network is to be able to communicate node information to the destination for storage or further processing [8]. The performance level of the routing is reflected in the delivery ratio, which should be as high as possible, preferably 100% for the routing algorithm to actually guarantee all messages reach their destination. Delivery of messages is guaranteed either at a routing level or at the MAC level. In some articles, the message delivery is not analyzed strictly from the routing perspective. Certain protocols' delivery performance is considered when the MAC layer is simulated as well, together with the ability to detect receipt failure through the ARQ technique and the ACK and NAK messages and retransmit data.

8. Scalability. Ad hoc networks as well as sensor networks have varying size and are forecast to reach sizes of thousands of nodes in the near future. This is only possible if routing algorithms allow network growth, without influencing network performance when new nodes join. This property is called scalability. Because scalability is not measured in a particular way and it depends on the outcome of a certain algorithm or protocol simulation, stating that an algorithm is, or is not, scalable is rather subjective. Algorithm simulations can be run under ideal conditions and may not even take mobility into consideration, therefore what may seem a scalable algorithm under certain constrictions, can eventually prove otherwise. Here, scalability is classified as low, medium or high. Low, when the network which uses the protocol in discussion cannot grow beyond a relatively small size. Medium, when the network does not perform well over a certain size threshold or when size is restricted by a certain condition (density or topology). High, when the network's performance is not influenced by size.

9. Overhead. The term 'overhead' refers to excessive traffic and operating expense needed to accommodate network demands. The existence of a high amount of network traffic, as a result of the design of the routing algorithm, leads to a combination of unnecessary or indirect resource expenditure, such as computation time and energy, memory and bandwidth. Traffic overhead, translated into large or numerous excess packets, therefore increases bandwidth consumption and data processing requirements. According to this we can classify the overhead as: packet overhead and processing overhead, each having a certain degree: low, medium or high, as explained below.

9.1 Packet overhead: When large or numerous packets are sent in a network, excess bandwidth is consumed. Numerous packages are sent when the routing algorithms use excessive beaconing or signalling packets. Large packets are sent when information is piggybacked or when tables with node positions and path costs need maintenance at each node. To characterize packet overhead level, we will use the following: low - means light messages and no signalling beacons (unicast

transmissions), medium – refers to a balance between packet size and packet number, high - comprises both large and numerous packets (unicast, multicast, broadcast).

9.2 Processing overhead: Processing requirements increase when the data transmitted in the network is encrypted for security purposes. Encryption and decryption consume energy and supplementary bandwidth. The amount of data processing at node level is also influenced by the number of computed operations (these being dictated by the routing algorithm design as well). To characterize processing overhead, we will use the following: low - translates into zero security and few demands on the processing unit, medium - means only one security method is used or data aggregation is employed, high - reflects a lot of processing activity and the use of multiple security methods. [7]

10. Adaptive to mobility. Ad-hoc networks and sensor networks are currently being adapted to serve the needs of more demanding applications and this implies nodes being mobile. Though early geographic protocols were designed for static ad-hoc networks only, it is now expected that routing should be able to take place in dynamic environments too. If the monitored events manifest no movement, then the routing algorithm is more stable - nodes sense and report their information and traffic is routed to fixed locations. If the events are dynamic and network topology changes, for example in a tracking application, nodes require periodic reporting and the routing algorithm has to deal with increased traffic, overhead and energy consumption [2]. Tables 2e and 2f provide information about protocols which were designed to satisfy mobility demands and protocols which were designed for static networks only. However, in the recommendations column of Tables 2e and 2f, one can find mobile protocols which are not recommended for dynamic applications. The reason is that protocols sometimes trade-off important qualities to be successful in mobile environments, making them less desirable for certain demanding applications.

11. Additional data (such as Network Type, Network Recommendations (size/density/mobility), Transmission Type). Geographic routing protocols like the ones presented in Tables 2a-d were designed for a certain type of network, so a column has been dedicated to this specifically. Related to this aspect is the Network Recommendations column. Researchers have simulated these protocols and analyzed their performance under several network conditions (small/large number of nodes, sparse/dense networks, under static/mobile conditions). Thus, suggestions could be made for the type of network recommended for implementation, information which can support the application suggestions as well. The Transmission Type field sheds light on the type of communication used by nodes for routing purposes (Node to Node (N2N), Sink to Nodes (S2N), Nodes to Sink (N2S)). This information is presented because it has illustrative purposes for the packet overhead (as discussed in the Overhead section). Depending on the number of destinations, the transmission can be unicast, multicast, broadcast or anycast (Figure 6). Unicast refers to a single destination transmission. Multicast is used to deliver a

packet simultaneously to a group of destination nodes. Broadcasting aims to deliver the information to a single destination via mass transmission.

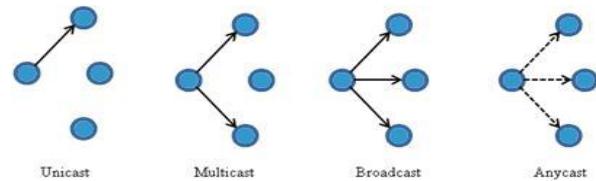


Figure 6. Transmission Types

Above routing parameters are necessary to characterize and compare the performance of geographic routing protocols. Depending on these described features, the protocols in Section 5 have a certain degree of compatibility with each application area presented in Section 6. To determine the compatibility degree, or simply for further research, presumes a difficult and otherwise time consuming analysis without the aid of the present survey. Of course, the work of this paper might not be enough for practical purposes because the behaviour of each protocol has been studied only under simulated theoretical network scenarios, sometimes unrealistic or insufficiently detailed to match the desired application. To be able to choose the most suitable protocol would therefore imply more study of the protocol itself. However, to be able to efficiently focus the research in the correct direction, one would need to know which of the existing protocols is more suitable, at least theoretically, to a certain area of application, from all the points of view expressed in this section. To do so, a comparison has to be made, as in the tables in Appendix 1, which serve this purpose.

5. Position-based Routing Protocols and their Comparison

This section presents some of the most important position-based protocols proposed prior to this paper. Many of them are geographic routing protocols. The protocols' names are abbreviated due to space limitation and are presented, in the chronological order of their publication, in Table 1. The position-based protocols are then presented according to the category they belong to as they are classified in Table 3. Some of the algorithms have characteristics which place them in more than one category, but, for simplification purposes, they are presented here as belonging to just one, while the rest of the features are just described. The algorithms are just shortly explained in this section in terms of functionality without referring to the characteristics in the previous section. Few comments are made about data aggregation information, cross layer implementation, motion model (for mobility), assumptions, downsides and objectives. Regarding data aggregation, some geographic routing protocols use aggregation processes which decrease the energy spent on multiple path transmissions, but increase processing overhead. In WSN especially, there are situations when multiple sensors record the same information if they are situated in the proximity of the same event. The information has to be sent towards a destination, perhaps a sink, on multiple paths. This redundancy should be avoided to save energy. Information from similar packets can be

combined by using certain functions at node level: such as suppression, minimum, maximum or average [2].

The information in Section 4 is used in the Tables 2a-f which can be found in the Appendix 1. These tables compare the investigated protocols based on the routing issues which applications in certain areas may refer to. Tables 2e and 2f are devised to separate protocols that are adaptive to mobility from those that are not and compare these protocols from other points of view than the previous tables: 2a-2d. With the help of these tables, suitability for specific applications is properly suggested in Section 6. Also, the tables can be very useful in research analysis for those who are not very familiar with position-based or to geographic routing or to those who simply want to compare the advantages of the protocols in this study.

Table I. Position-Based Protocol Names and Abbreviations

-**MFR** - Most Forward within Radius (1984)[22]
 -**DREAM** - Distance Routing Effect Algorithm for Mobility(1998) [33]
 -**GFG** - Greedy Face Greedy (1999) [39]
 -**Face Routing** - also known as Compass Routing II or perimeter routing (1999) [23]
 -**DIR** - Compass Routing Method/Perimeter Routing (1999) [23]
 -**MECN** - Minimum Energy Communication Network (1999) [52]
 -**LAR** - Location-Aided Routing protocol (2000) [24]
 -**GLS** - Grid or Geographic Location Service (2000) [38]
 -**GPSR** - Greedy Perimeter Stateless Routing (2000) [48]
 -**SMECN** - Small Minimum Energy Communication Network (2001)[53]
 -**GRUPI** - Geographic Routing Using Partial Information (2001) [45]
 -**GEDIR** - Geographic Distance Routing (2001) [25]
 -**GEAR** - Geographic and Energy Aware Routing (2001) [34]
 -**GAF** - Geographic Adaptive Fidelity - Geography Informed Energy Conservation for Ad-hoc Routing (2001) [54]
 -**SPAN** - An Energy Efficient Algorithm for topology Maintenance (2001) [26]
 -**TMNR** (Terminode Routing) (2002) [40]
 -**SPAAR** - Secure Position Aided Ad-hoc Routing(2002)[35]
 -**SPEED** - A Real-Time Routing Protocol for Sensor Networks(2002)[27]
 -**GOAFR** - Greedy Other Adaptive Face Routing – It was created after investigating and improving face routing. Face routing was extended through: BFR (Bounded Face Routing) and AFR (Adaptive Face Routing). Other related algorithms are OFR (Other Face Routing), BOFR (Bounded Other Face Routing), OAFR (Other Adaptive Face Routing), GAFR (Greedy Adaptive Face Routing) and GOAFR, all mentioned in the same paper. GOAFR is the most efficient. GOAFR has been improved through consecutive versions: GOAFR+, GOAFR++ and GOAFR PLUS-ABC. (2003) [49][55]
 -**LABAR** - Location Area Based Ad-Hoc Routing for GPS-Scarce Wide-Area Networks (2003) [56]
 -**CBF** - Contention-Based Forwarding (2003) [28]
 -**IGF** - Implicit Geographic Forwarding (2003) [41]

-**GRWLI** - Geographic Routing Without Location Information (2003) [29]
 -**ARRIVE** - Algorithm for Robust Routing in Volatile Environments(2003)[57]
 -**TBF** - Trajectory Based Forwarding (2003)[42]
 -**ALARM** - Adaptive Location Aided Routing Protocol-Mines(2004)[36]
 -**BLR** - Beacon-less Routing (2004)[46]
 -**DSAP** - Directional Source Aware Routing Protocol (2004)[58]
 -**EEFS** - Energy Efficient Forwarding Strategies for Geographic Routing (2004)[43][59]
 -**TTDD** - Two-Tier Data Dissemination (2005) [47]
 -**I-PBBLR** - Improved progress Position Based BeaconLess Routing (2005) [30]
 -**BGR** - Blind Geographic Routing (2005) [60]
 -**SWING** - Small World Iterative Navigation Greedy Protocol (2006)[31][32]
 -**AODPR** - Anonymous On-Demand Position-based Routing in Mobile Ad-hoc Networks (2006) [37]
 -**LOSR** - Local Optimal Source Routing) (2007) [50]
 -**GREES** - Geographic Routing with Environmental Energy Supply (2007)[44]
 -**SWING+** (2008) [61]
 -**EEGR** - Energy Efficient Geographic Routing (2008) [62]
 -**MDSAP** - Modified Directional Source Aware Routing Protocol (2008) [63]
 -**MACQP** - Multiple Ant Colonies Query Protocol (2008) [64]
 -**LED** - Least expected distance (2009) [65]
 -**EGR** - Energy-Aware Geographic Routing (2009) [66]
 -**ORF** - Optimal Range Forward (2009) [67]
 -**OFEB** - Optimal Forward with Energy Balance (2009) [67]
 -**RGRP** - Reactive Geographic Routing Protocol (2010) [68]
 -**EBGR** - Energy-efficient Beaconless Geographic Routing (2010) [69]
 -**EAGPR**-Energy Aware Geographic Routing Protocol (2010) [70]
 -**AeroRP** - Aeronautical Routing Protocol(2011) [71]

5.1 Geographic algorithms (for routing):

MFR: It is a progress-based algorithm, in which data is forwarded to the neighbour with the greatest progress (node A in the Figure 7). Its objective is to maximize obtainable expectable progress in a certain direction. If no node is in the forward direction, within the range of the sender, the message is sent to the neighbour node with the least backward progress. This algorithm minimizes the number of hops, but doesn't minimize energy consumption. In inhomogeneous node density (for uniform Poisson distribution of nodes), it is recommended for short range transmission because of the low possibility of packet collision. In [25], another version is proposed (f-MFR), which uses flooding to guarantee delivery and eliminate looping. F-MFR is not presented in the tables.

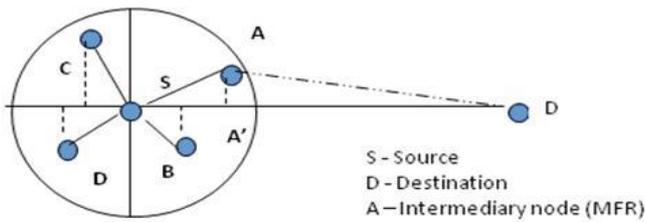


Figure 7. Illustration of progress with MFR

FACE: It is presented, as a method which guarantees delivery. Face routing proceeds along faces of planar graphs and along the line connecting the source and the destination, so the underlying network has to be a planar graph. It uses the Right Hand Rule and has to explore the complete boundary of faces (Figure 8). It is unsatisfactory because the delivery of the message takes place in a number of steps equal to the number of network nodes, which is similar to flooding.

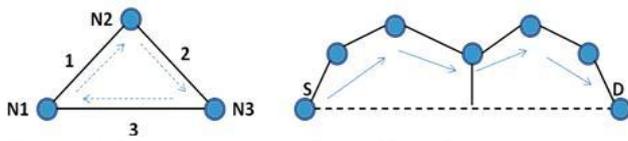


Figure 8. Illustration of the Right Hand Rule and progress with Face Routing

DIR: This algorithm uses the following method: the sending node uses the information it has about the destination to calculate the direction in which to forward the message. It is also named Compass routing because it minimizes the angle between the computed direction and the direction source-destination (Figure 9). Another version of this method is proposed in [25], enhanced through flooding (f-DIR), which guarantees delivery and loop freedom under reduced flooding rates. (f-DIR is not presented in the tables)

GPSR: Each node of the network maintains a neighbour table, periodically updated through beacon messages – this results in a lot of data traffic; source’s location is piggybacked on all data packets; it is tested in flat (2-D) topologies; it uses 2 methods for forwarding data: greedy forwarding and perimeter forwarding (right hand rule). Nodes try to create a map of the neighbours that have tentative routes to the destination. A node sends the packet to neighbour nodes closed to its perimeter region. After perimeter forwarding, routing states are collected and cached in the nodes for reuse in route recovery. It performs well in a scattering network with few neighbours. It also guarantees delivery, but assumptions such as an ideal 802.11 MAC layer and a static topology. For the mobility study, the random waypoint model was used.

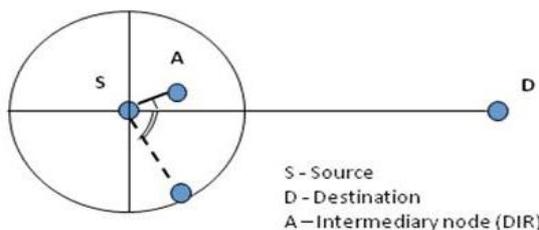


Figure 9. Illustration of progress with Compass Routing

GEDIR: The basic protocol (V-GEDIR) uses a greedy routing scheme based on geographic distance and a failure criterion. (The node positions are assumed to be known through GPS.) It drops the message if the best forwarding choice of the current node is to return the message to the originating node. The V in the name comes from the Voronoi diagram, which is used to determine neighbour nodes by intersecting it with the circle/rectangle area of the destination position. Another assumption is of a simplified version of IEEE 802.11 MAC. The algorithm has been proposed with different forwarding methods: one-hop GEDIR (GEDIR), 2-hop GEDIR (GEDIR-2), flooding GEDIR (GEDIR-f) and 2 hop flooding GEDIR (2-f-GEDIR). The hybrid single-path/flooding GEDIR was designed for mobility issues and to provide guaranteed delivery for the static case. The flooding is of partial nature, restricted to a number of hops. In terms of mobility, it is assumed that move with a given probability, towards a random destination, in a straight line, with a random speed.

SPEED: Designed for a longer network lifetime, the routing component (stateless geographic non-deterministic forwarding – SNFG) uses 4 modules: beacon exchange, delay estimation, a neighbourhood feedback loop and backpressure rerouting (sent to source to find alternate routes). The forwarding nodes are calculated from the neighbour nodes (so within range R) also having to be at least k distance closer to the destination (node F in the Figure 10). If no candidates fulfil the criteria, the packet is dropped. The forwarding candidates are divided based on the single hop delay giving higher probability to the nodes with the highest relay speed. The protocol tries to ensure a certain speed for each packet sent, so that the application can have an idea about the end-to-end delay between nodes. End-to-end real-time communication is achieved using a combination of feedback control (to guarantee a per node delay in steady state) and non-deterministic QoS-aware geographic forwarding with a bounded hop count (which helps react to congestion and loads).

GOAFR: It is a combination of greedy forwarding and Other Adaptive Face Routing and makes use of a distance-bounded face traversal; the face is traversed on both sides using the left and right hand rule, for a bounded distance; if the condition to return to greedy mode is not satisfied, it increases the bound. It is considered worst-case optimal and average-case efficient. A certain minimum density per unit disk is critical!

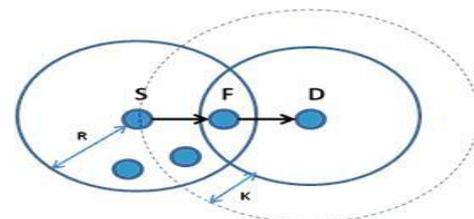


Figure 10. Forwarding areas for the SPEED protocol

CBF: It is a beacon-less algorithm which consists of two forwarding phases: contention, in which a node is determined as next hop through a timer-based function, and suppression in which other candidates are held back

from forwarding the packet. The suppression process can be implemented through area-based forwarding, using either a circle or the Reuleaux triangle, or through active selection (Figure 11). In area based suppression, no recovery strategy is mentioned after two more broadcasts. Active selection makes use of the 802.11 MAC. A Request to Forward (RTF) message is sent by the source to activate the timers of nodes and the Clear to Forward (CTF) reply is sent when a timer has expired and forwarding can take place through that certain node. The drawbacks of this algorithm are the lack of a recovery method when forwarding in greedy mode in an empty area and the packet overhead created by broadcasts.

IGF: This beacon-less routing protocol with Dynamic Forwarding Delay (DFD) tries to balance energy consumption in nodes considering the movement of the forwarding area (so distance) when no node is available. The IEEE 802.11 MAC layer is modified to perform the selection of the forwarding node by using an Open Request To Send (ORTS) broadcast to a forwarding area (a sector is used). The Clear To Send (CTS) reply is received by the sender when a node's timer expires announcing it is the next hop. When the node receives the packet it sends an acknowledge message (ACK). If the forwarding area is empty (no CTS is received), the forwarding area is moved, but no other recovery strategy is implemented. Through the timer function implementation, nodes with more power are favoured, so energy availability is taken into account.

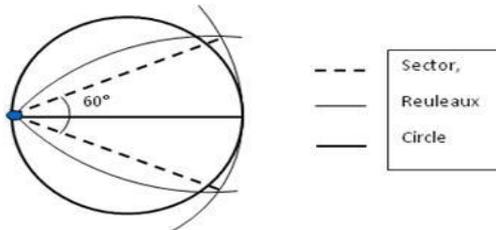


Figure 11. Forwarding areas

GRWLI: It is a virtual coordinate-based routing algorithm with virtual coordinates that do not have to match the geographic location of the nodes. Assumptions are made about the existence of a service which translates identifiers into location coordinates (such as GLS or a distributed hash table implemented on top of the routing system) – hence achieving the objective of routing without location information. It considers the topology as a graph, not a tree. The protocol has three stages which change as initial assumptions change. During the first stage, it is assumed that perimeter nodes know their location, while non-perimeter ones are assigned virtual coordinates. Due to the force which pulls neighbours together (according to graph theory) and nodes tend to move towards the perimeter nodes closest to them until the algorithm converges to a steady state. During the second stage, perimeter nodes do not know their location only that they are on the perimeter. A triangulation algorithm is executed and 2 nodes are designated as bootstraps. This will enable the algorithm to compute the coordinates of the entire perimeter. The third stage assumes no location information and uses a criterion to decide if they are perimeter nodes. Being adaptive to mobility, overhead is dependent more on this aspect than on network size.

ARRIVE: It is a probabilistic algorithm which uses localized information and leverages high node density and the broadcast medium to achieve robust routing. One of its goals is secure message transmission. It is based on a tree-like topology, with the sink as a root. It uses a breadth first search beaconing algorithm to initialize levels, parents and neighbour state information. The nodes evaluate their neighbours and parents to make probabilistic forwarding decisions (a method entitled beam-forming which considers bandwidth, energy levels and distance to destination). Different packets representing the same event can be sent on multiple routes. Event aggregation is optional. The algorithm adapts to large node failures while the trade-off is moderate energy consumption and transmission latency.

I-PBBLR: This algorithm uses a beaconless approach, in which sender nodes make non-deterministic routing decisions, based on an improved progress metric (the product between traditional progress and the cosine of the angle). Assumptions are made about the availability of a positioning system, the UDG communication graph, bidirectional links and omni-directional antennas. For mobility, the random waypoint model is used. Regarding the routing, the nodes determine the next hop through contention at transmission time, knowing location information only about the destination and the prior sender. If nodes are in the forwarding area, they apply Dynamic Forwarding Delay (DFD) prior to relaying the packet. If they are not, they drop the packet. The node which computes the shortest DFD, based on the positions of current and previous sender nodes and of destination, broadcasts the packet to all its neighbours. The rest of the nodes in the forwarding area cancel their scheduled transmissions of the same packet. It inherits the properties of greedy forwarding, but improves the performance in sparse networks.

BGR: Assuming a positioning system is available, the algorithm aims to minimize energy consumption. It is a beacon-less geographic routing algorithm which forwards packets towards the destination in a certain forwarding area, while nodes in the network compete through timers to become the next hop. The node whose timer stops first continues the forwarding process. Simultaneous forwarding is prevented through a novel strategy called Avoidance of Simultaneous Forwarding (ASF) which uses the stored number of hops in the packet header to compare it with the number of hops stored in the node. Depending on this comparison, the nodes in the forwarding area cancel or continue their timing. The algorithm also implements a recovery strategy by changing the forwarding area (60 degrees left or right). The forwarding area is an implementation-dependent choice.

GREES: It makes routing decisions based on realistic wireless channel conditions, packet advancement to destination, residual energy battery level and environmental energy supply. It uses piggybacking in Hello-messages to update each node and his neighbour with the energy status. As a result, it maintains higher mean residual energy among nodes, demonstrates gradual acceptable degradation on end-to-end delay, does not

compromise on performance and achieves better load balancing.

EEGR: This geographic routing algorithm takes into account sensor position error, but does not make some assumptions for simulation purposes: of an ideal, lossless and collision-free MAC and of uniformly distributed nodes with a randomly positioned base station with no location error. Nodes' location is estimated with a certain error ϵ . Node A for example can be located within any of the three surfaces S1, S2 and S3, in which communication is possible, probable and impossible (as in Figure 12). So depending on these cases, the communication probability is calculated based on the location error. The algorithm uses a metric which defines communication costs between neighbours. It sends messages along paths having the best trade-off between communication probability, progress and energy consumption. Shortest path, from sensor to base station, can be computed with Dijkstra algorithm. In low density consumes less than 30% of additional energy, in high density, less than 20%, thus optimizing energy consumption in networks in which sensors are inaccurately located.

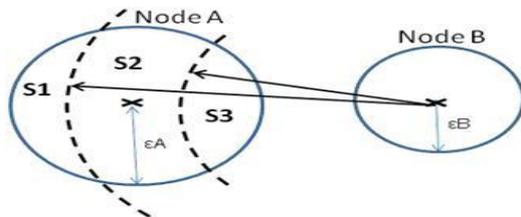


Figure 12. EEGR forwarding cases for the communication probability calculation

LED: This algorithm takes into account the inevitable presence of location errors in the localization process inherent to geographic routing. By incorporating location errors into the routing objective function, the algorithm maximizes the probability to achieve minimum power consumption from source to destination. By determining the optimal next forwarding position which optimizes the energy consumption over a single hop, the optimization of the energy over the total path is achieved. As a downside, the algorithm is not fully developed to the level of a protocol hence its study is theoretical based on assumptions of a static, stable uniform random network without obstacles and having nodes with accurate symmetric radio ranges. Nonetheless, the algorithm's consideration for location errors makes it very valuable for further research.

EGR: This energy efficient algorithm is designed for mobile environments and makes use of residual energy information in greedy and recovery mode alike. Assumptions of GPS or a location service mechanism are made which can provide the location information for the destination, while that of the neighbours is obtained through beaconing. Also, because nodes are considered mobile, the random waypoint model is used for simulation. (The simulations include the MAC 802.11). In both basic mode as well as when handling voids, the forwarding node is chosen to balance energy consumption by maximizing a weight function which takes into account distance progress (for greedy routing) or angle progress (for face routing) and residual energy. Figure 13 illustrates how the new perimeter routing (based on the right

hand rule) may choose A2 instead of A1 as forwarding node due to more residual energy. Again at this point A2 can choose among A1, B1 or B2, and may choose B2 on the same basis. The algorithm needs further investigation in terms of scalability and node density.

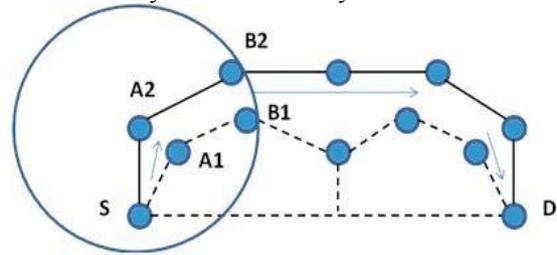


Figure 13. Example of a new perimeter with EGR

ORF and OFEB: Their target is to prolong network lifetime, by optimizing energy consumption and balancing traffic load. ORF is based on the derivation of the optimal node transmission range which results in minimization of the total energy consumed by the transmission in all hops. OFEB achieves energy balance by making use of the principle in ORF and, in addition, considering the residual energy of each node in finding the optimal next forwarding node. As network lifetime is prolonged, these protocols can very well be implemented for Ad-hoc wireless network applications which need to preserve energy in remote sensor nodes.

EBGR: It is designed for highly dynamic scenarios with changing topology in which location information is known. The algorithm aims to provide loop-free, energy-efficient sensor to sink routing at low communication overhead. The forwarding process avoids beacons, but uses the RTS/CTS handshaking mechanism and calculates the ideal next-hop relay position (N_i in Figure 14) on the straight line between source and destination based on an energy-optimal forwarding distance. Each forwarding node chooses as next hop the neighbour closest to the ideal next hop relay position (in the figure node N1) within a predefined relay search region. In the recovery mode beaconless angular relaying is employed with two phases: selection and protest. The selection is based on RTS/CTS between source and neighbours in counter clock order, while in the protest phase, the first node that protests is selected as the next hop relay. The algorithm also tries to provide energy efficient routing in the presence of unreliable communication links by employing blacklisting and a discrete delay function. The performance is analyzed in three scenarios: a mobile scenario (in which a random walk mobility model is used for simulation), a random sleeping scenario (static case) and a high variant link quality scenario (for a static, active network with changing link quality).

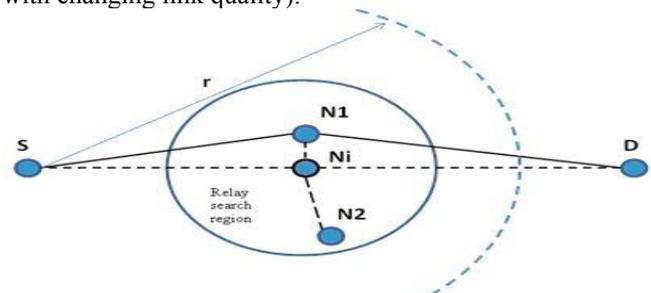


Figure 14. Greedy forwarding in EBGR

EAGPR: It is a geographic routing algorithm based on greedy forwarding. Nodes have only local knowledge of neighbours' position and energy levels and the location of the destination. The forwarding decision is based on distance calculations and energy levels above a certain threshold. The packet is forwarded to the neighbour closest to destination and with the highest energy level, by first adjusting the transmission power. The objective of the algorithm is to prolong the lifetime of the sensors and hence the network lifetime. The study of the protocol is made under various network sizes and claims to be scalable and conserve more energy than protocols as DSR or AODV.

AeroRP: It is a domain specific routing protocol for aeronautical networks which targets to outperform MANET routing protocols. Its operation is based on an initial neighbour discovery phase – the beacon mode – in which neighbour coordinates and velocity can be detected. The information can be updated through overhearing. Communication beacons do not have to be periodic, as this promiscuous behaviour of sharing trajectory information is exploited. The neighbour tables are used to calculate the time to intercept (TTI) used in forwarding decisions to inform on how soon the potential neighbour will be within transmission range. Nodes can ferry (queue indefinitely until a node with lower TTI is found), buffer (queue for a specific time) or drop the packets depending on the mode of the routing protocol. The assumptions of the protocol analysis are not realistic as the randomly distributed network nodes have to deliver the information to one static centrally located sink, which can be a bottleneck. In addition another downside is that the performance is influenced by node density. (Simulations include the MAC 802.11b.)

GEAR: The protocol assumes a localization system and targets an increased network life time. It consists of two forwarding phases: forwarding the packet towards a targeted region and disseminating the information within that region. The first phase routes packets based on distance to destination. Each node maintains an estimated and a learned cost value for each destination. The learned cost value is used for forwarding to nodes which are further from destination, to avoid holes in the network. When the learned cost is the same with the estimated value, there are no network voids. The dissemination stage is based either of recursive geographic forwarding for dense networks (as described in section 4, under packet forwarding) or flooding in sparse networks (to avoid the loops which would otherwise occur). Realistic wireless channel conditions are not accounted for, but nodes' residual energy is considered.

EEFS: As most geographic routing algorithms, EEFS assumes a positioning system to account for the location knowledge. It assumes nodes are randomly distributed in the network and aims to improve energy efficiency considering distance and reception rate in the routing decisions. The study is performed with and without ARQ, considering aggregation possibilities. Neighbours are classified based on link reliability and neighbour selection (blacklisting) is used. Some neighbour links are weaker than others and some even have a different loss characteristic. A compromise between shortest path in

greedy forwarding and most energy efficient path has to be made by considering the transitional region between the two possible strategies. Blacklisting has to be carefully considered to not affect connectivity.

5.2 Geographic algorithms (to support routing)

GLS: It is a location service specifically for geographic locations. It is simulated with simple geographic routing and GPSR. It breaks up the network area into a hierarchical system of squares forming a quad-tree (as in Figure 15), where each n-order squares contain four (n-1)-order squares. It makes use of location information and unique, permanent, random allocated node IPs, so each node stores a table of all nodes within the local first-order square.

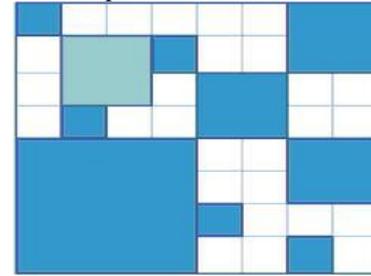


Figure 15. Hierarchical zones of the GLS (Quad-tree)

The use of periodic broadcasts as location updates increase with network size. The success rate degrades linearly so scalability is compromised when it comes to large networks (metropolitan size). For mobility simulation, the random waypoint model is used.

MECN: It is a protocol which sets up and maintains a minimum energy network by assuming the nodes to be low power GPS devices with active/sleep periods in synchronized mode for the entire 2-D network. Another simplifying assumption is that of a fully connected network, with no underlying infrastructure, with a single sink – possible point of failure. The algorithm is based on identifying a relay region for each node as in Figure 15. In the relay region there are those nodes with which communication is energy efficient. By taking the union of all the relay regions of a certain node, the enclosure of that node is formed. The 'sub-networks' identified by the algorithm contribute to the global purpose of finding minimum energy optimal paths for less energy consumption and an increased lifetime. The protocol consists of two phases: the first one is the construction of a sparse graph, an enclosure (see Figure 16), which encloses all transmit nodes in the graph; the second phase consists in finding the optimal links through Bellman-Ford shortest path algorithm and a power consumption metric. If the network is dynamic, the protocol's self-reconfiguration helps adapt to node failure and deployment of new sensors.

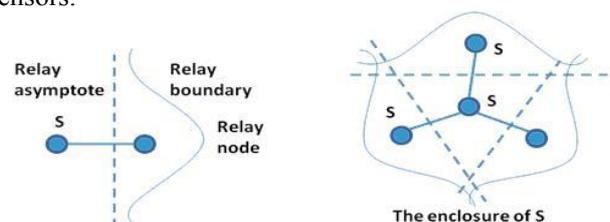


Figure 16. Relay area and enclosure for MDSAP

SMECN: This is a protocol which can be used with other routing protocols. It is simulated with a modified version of AODV and can be simulated with geographic routing protocols as LAR and DREAM as well. This protocol is a variant of the MECN algorithm considering obstacles between nodes and constructing smaller sub-graphs. It makes assumptions of a fully connected 2-D static network and of random uniformly distributed sensor nodes. The goal of the algorithm is to determine the enclosure graph for minimum energy paths. It is less complex, more realistic and more power efficient. The number of hops per transmission decreases and so does the complexity of the constructed graphs. The trade-off however is the overhead which exceeds the MECN's one. The protocol can be implemented for mobility, but the simulated scenario uses a fixed network. SMECN is not recommended, under the simulated scenario, for Internet and telephone networks, but for environment-monitoring sensor applications.

SPAN: This protocol operates under the routing layer and above the MAC and physical layers and is designed to conserve energy and increase network lifetime. (For simulation purposes, the 802.11 MAC is employed, in power saving mode with failure feedback and interface queue traversal - to remove unresponsive packets). It is a coordination technique to reduce energy consumption which can be implemented with other routing protocols. In the original paper it is implemented with geographic forwarding. The technique relies on the following: each span node decides by itself whether to sleep or join the forwarding backbone, as coordinators, based on local topology information. When a void is encountered, packet is dropped. Loss rate is low both for mobile and static networks, lifetime is doubled and connectivity is preserved. It improves routing throughput and packet delivery latency. For mobility, the random waypoint model is used.

LOSR: It is an energy-efficient mechanism for existing geographic routing protocols (GPSR is used in the original paper, as GPSR-SRO). Its objective is to reduce energy consumption by selecting energy efficient paths and using node neighbours which are not the best forwarding option in terms of progress towards destination. It annotates, through a source header (SRH), the sent message with the list of nodes that must be traversed. The SRH always leads to a node that provides advance. Dijkstra's algorithm is applied to the sub-graph made of the neighbours of the current node. Automatic Repeat reQuest (ARQ) is used and retransmissions are considered as a realistic source of energy consumption.

TBF: It is a hybrid forwarding method used to transmit packets along a predefined parametric curve by encoding this information in the message, at the source (see Figure 17). The curve can be a simple or a composed trajectory. TBF is suggested as a layer in position centric ad-hoc networks as a support for various routing methods. TBF can be used in unicast, multipath, broadcast and discovery applications, providing resilience against imprecise positioning and in sparse networks. The downside of TBF is that trajectory determination is not a

localized process, so valuable network resources can be consumed on it.

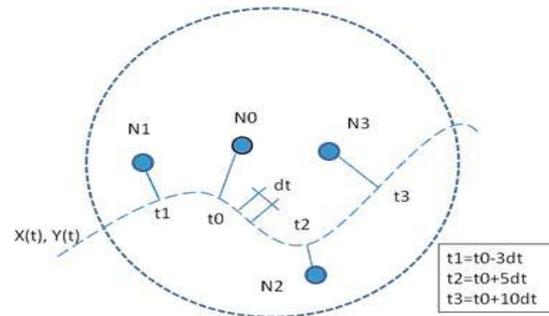


Figure 17. Forwarding on a curve, where N0's neighbours within a certain distance are in a dashed circle

5.3 Topology-Based Routing Protocols (with route discovery)

LAR: It makes assumptions of a 2-D plane, of GPS equipped nodes or the availability of another location service, of equal node range, of location error, of no congestion, no transmission error and no delays. Also, only one sender and one destination are presumed. The objective is to reduce the number of nodes to which the route request is propagated. It is a routing protocol with two proposed methods: LAR1 and LAR2, both illustrated in Figure 18. Route discovery is used. LAR1 limits the search area for a new route to a 'request zone' whose definition can be varied. The sending node forwards the message only within the request zone and neighbours outside the area are not addressed. Within the limited sector, flooding is used. LAR2, in addition to LAR1's algorithm of partial flooding, uses a forwarding criterion: the sending node always forwards the message to all nodes closer to the destination than itself. For mobility, nodes are assumed to have random directions, uniformly distributed speed, with no pause and to bounce off the boundary.

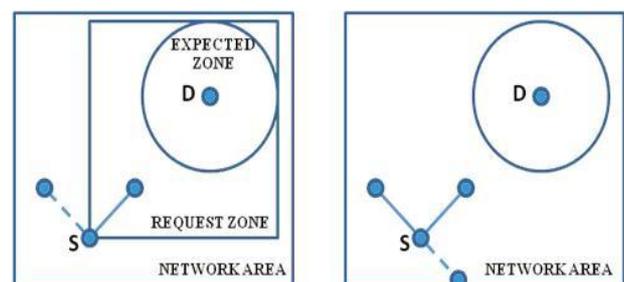


Figure 18. a. Progress with LAR1 (source outside the expected zone)
b. Progress with LAR 2 (forwarding option further away than source)

ALARM: It is a hybrid, adaptive to mobility protocol which uses LAR and directed flooding. It introduces the flood horizon, the number of hops to be flooded past the mobility hot spot. Its performance is identical to the component protocol that performs best in that situation. It uses link duration feedback at each node to determine the appropriate forwarding method and it adapts the operation on current network mobility conditions. Packet overhead increases with mobility.

DREAM: It is a position-based routing protocol, but not a purely geographical one because of its proactive approach. By using a new mechanism of dissemination and update of location information as well as routing tables for all the nodes in the network, DREAM can be categorized as a proactive routing method. Its “distance effect” method considers the need to update location tables with less frequency for further situated nodes or with increased frequency for mobile nodes. Control packets (with an assigned life time based on travelled geographical distance) are used to determine node distance S-D. Similarly to LAR, an expected zone of radius r is defined as $(\text{current time} - \text{timestamp } S \text{ has on } D) * \text{maximum node speed}$. According to it, the direction is given by the distance line S-D and the alpha angle (see Figure 19). The algorithm does not rely on large amounts of control information or on delay creating routing discovery methods. However, because it is a direction based approach, a recovery method is necessary when the destination node is not in the given direction. The recovery procedure, i.e. flooding, can influence the performance of the basic algorithm, but it is not included in the specifications.

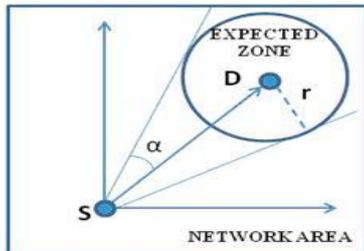


Figure 19. Illustration of progress with DREAM

GRUPI: It is a real-time, asynchronous algorithm in which each node has a distance-dependent aggregated view of the network topology (a geometric way of viewing routing operations called the Voronoi view). It takes into account location errors and node failures. It requires nodes to partially store routes towards destinations in a routing table (the routes for which they are concave) and it applies greedy forwarding. Nodes further away from destination need to know less of the network topology than closer-to-destination nodes. The route discovery process is used for closer nodes, to update routing tables – this can be done such as routing tables to be cycle-free. It uses 2 route discovery strategies: breadth first and depth first search. The algorithm can be adapted for mobility, by extending it with the use of the tear-down protocol and the random way mobility model needed for simulation.

SPAAR: It is a position based routing protocol which uses geographical information and improves the security of mobile ad-hoc networks. Every message sent in the network is signed with a private key and encrypted with the public key of a neighbour. A high level of security is achieved also through allowing nodes to receive routing messages only from one-hop neighbours. Each node which participates in the routing process has to have a private/public key pair, a certificate binding its identity to its public key and the public key of the certificate server. The assumption is that there is one single certificate

server – possible point of failure. Routes to specific destinations are found by sources broadcasting a Route REquest (RREQ) encrypted with a group encryption key. Intermediate nodes check if they or other neighbour nodes are closer to destination and forward the request towards the destination. Intermediate nodes also record in their route cache the address of the neighbour from which they receive the request, thereby establishing the route back. The destination uses the route back to send the Route REPLY.

BLR: This is a beacon-less algorithm with reactive routing. It assumes GPS equipped nodes or another location service, assumes the ideal UDG communication model, bidirectional links, omni-directional antennas and considers that each node has information about the maximum radius and delay per hop made available. The objective of the algorithm is to reduce routing overhead, thus paths through one node are aggregated. It selects a forwarding node in a distributed manner by broadcasting data packets to a forwarding area. From the nodes, only one is selected to forward the packet. The optimization of this protocol consists in applying a concept of Dynamic Forwarding Delay (DFD), in such a way that the forwarding node is chosen according to the shortest forwarding delay. Optionally, there is a promiscuous mode in which a node can function, as well as a backup mode when a forwarding area is found to be empty. To cope with inaccurate location information it utilizes a topology-based reactive routing algorithm (RLR) in the vicinity of the destination. Six route requests are flooded in six directions (partial flooding), separated by 60 degrees at twice the range from the source.

DSAP: It consists of two algorithms, one to find the destination and one to route the packet. After collecting the information from distributed multiple sensors, based on the information, the routing protocol forwards the packet in the direction of the destination via the nearest neighbour. It makes use of unique IDs which inform on how far a node is from the network perimeter in each direction (directional value (DV)). Nodes can compute the relative direction of other nodes based on this ID. The study is made on a fixed number of nodes (fixed topology) and aims to increase power efficiency and network lifetime.

SWING: Making use of assumptions regarding a location service and an ideal MAC, its objective is to alleviate the effect of location errors on routing. It is a purely greedy routing protocol with the data transmission having two stages: route discovery and data delivery. The local minimum problem is fixed by using 2 methods: first it constructs a virtual small-world network in which each node sets up virtual long links (VLLs) with remote nodes; secondly it uses virtual force (VL) - based greedy routing. As a downside route establishment is longer than in other protocols.

AODPR: It is a security oriented protocol which takes two measures to protect the network from malicious attacks: keeps routing nodes anonymous by using a Temporary Identifier (Temp ID) computed from time and

position of a certain node and the concept of Virtual Home Regions. Each node is located in a VHR, a geographical region around a fixed centre which knows its geographic position through GPS. Nodes report to Position Servers (PS) to keep position information secure. AODPR is an on-demand protocol which uses route requests and route replies (dynamic handshake) and estimates the minimum number of hops to destination. The value is carried and updated by each node which forwards the route request. The updated value is compared to a calculated value h' and the result influences whether the route request is forwarded or dropped. Calculations of the h' are made depending on the distance from node to destination and on the transmission range of the nodes. It has higher scalability than SPAAR and smaller packet overhead.

MDSAP: It is a proposed modified version of DSAP and it makes a compromise between the shortest path and the maximum power. It considers two types of nodes: fixed beacon nodes (B-nodes) and mobile nodes (M-nodes). Messages are assigned different levels of priority and different routing to each: high priority messages can take the path with the maximum power (not the shortest necessarily), low priority can take the shortest path (with no consideration of power), medium priority can take the shortest path, but having a certain energy threshold. Aggregation is optional, but in the tables, processing overhead is considered.

SWING+: As in the previous version of the algorithm, a location service is assumed, as well as allocation registration and lookup service. It is an improved version of the SWING protocol and it is the first geometric routing protocol applicable in 3D networks, so in non planar and non-unit-disk graphs, because it does not rely on face routing, guaranteeing delivery. It increases virtual connectivity and reduces local minima. However, a downside is the slow establishment of long links which is possible only in relatively static networks. Also, in dense networks, it should be run on cluster heads.

MACQP: Ant algorithm-based intelligent routing has been proposed successively over the years, as a type of proactive position-based routing for WSNs. However, the main idea of the algorithm which is inspired by the nature of ants and is supposed to find the best route to destination is based on queries: ant packets explore the possible routes from source to sink, making this a complex approach. Though nodes do not memorize more than their neighbours' positions (which can be periodically updated) and the position of the sinks (of which they are informed by the sink), nodes still consume energy on generating the ant packets. These packets explore the routes to destination, memorize the visited nodes, the selected edges and the position of the sinks. Packet overhead is created on global and local 'pheromone' updates and processing overhead on calculation of the weight of the current node to all neighbours (by pheromone value, residual energy and link cost) and on calculation of the forwarding probability. MACQP aims to solve the query-processing problem for replicated data in WSNs and therefore uses hierarchical division into clusters whose cluster heads perform data aggregation and encoding. Its objective is to maximize

network lifetime and minimize power consumption spent on query processing.

RGRP: It is a hybrid routing algorithm which combines a reactive mechanism and geographic routing which aims to find the shortest path and reduce communication overhead. It is a reactive position-based protocol that aims to improve communication cost by not using beaconing or table maintenance and benefiting from two types of route discovery packets RREQ and RREP with multiple functions. They are broadcasted to one-hop neighbours only by the source and destination and forwarded by the rest of the nodes. The shortest path to destination is calculated by coordinator nodes in two steps, both in the forwarding of the RREQ and of the RREP. Each time a node receives a RREQ or the RREP, it compares the distance of the paths it has been received on and discards the one arrived on the longer path. Route information and neighbour tables are not kept for a long time as they are created every time a new message needs to be forwarded.

5.4 Hierarchic Routing Protocols

TMNR: The protocol is based on collaboration and simplicity and it is a combination of two other protocols Terminode Local Routing (TLR) and Terminode Remote Routing (TRR). The protocol copes with load balancing, dynamicity and loops and holes in the network. Nodes receive the name of terminodes because they act as both nodes and terminals. TLR uses a simple distance vector routing protocol, while TRR uses simple anchored paths discovered with Friend Assisted Path Discovery (FADP) and Anchored Geodesic Packet forwarding (AGPF). It is adapted for dynamic networks and mobility is simulated through the restricted random waypoint model.

GAF: Two "algorithms" have been designed: a basic one, suitable for both static and low mobile scenarios, and one designed to adapt to fast mobility (GAF-b and GAF-ma). GAF is a position based protocol, but it is not designed to achieve the routing function. Its objective is to conserve energy and increase lifetime. Thus, the IEEE 802.11 MAC is used to manage power. It can operate over any ad-hoc routing protocol (in the original paper it is simulated with AODV). It makes use of a virtual grid system, three node states (see Figure 20): discovery, active and sleep and the technique called 'adaptive fidelity'. It identifies nodes that are equivalent from a routing perspective, in each grid cell, and adaptively turns off unnecessary nodes off for a constant level of performance while maintaining forwarding connectivity. An observation useful in implementation is that the higher the node density and the smaller the grids, the longer is the network lifetime.



Figure 20. State transitions in GAF (for energy savings)

LABAR: It aims to perform routing with a relaxation of the GPS equipment in sensor nodes. It therefore considers that GPS can be found only in certain nodes (G-

nodes), the rest having no location information. Assumptions are made about an open propagation environment and of equal node range for all nodes. It is a hybrid protocol combining the proactive and reactive approach with geographical routing. It makes use of two types of nodes (G-nodes and S-nodes) - with and without geographical knowledge of their own positions, as in Figure 21. This protocol consists of 3 steps: zone formation, virtual backbone formation and directional routing. The main idea is that G-nodes form a virtual backbone of the network. S-nodes are requested to belong to certain zones attached to a G-node. As soon as the S-node joins a certain G-node zone, his ID becomes known to that certain G-node. The G-node then maps the IP address to the geographical location. Zones are connected through a G-node called root. The source node uses the associated G-node to map the destination IP address and to calculate the vector from the G-node to the destination. The vector's direction is compared to each of the adjacent zones' direction and distance to determine the route with the least number of hops.

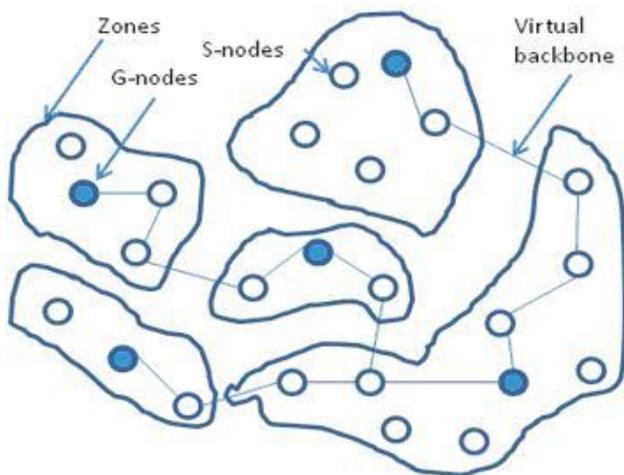


Figure 21. Backbone, Zones and Cluster heads (G-nodes) of the LABAR protocol

TTDD: This is position based protocol which disseminates data in the network using a grid and geographic greedy forwarding. The sensor network assumes sensor nodes with static positions and multiple mobile sinks. Each source node (sensor) builds its own two tier grid proactively, before receiving the sink queries. It then sets up the forwarding information at the nodes located in the grid points or as near as possible (dissemination nodes). The sinks query the sensors by flooding the local cell (tier) in which the sink is situated. The queries traverse the network only through the grid nodes. The sources use data aggregation and send the packets on the route they received the query, using the route information supplied by the query forwarding process, as illustrated in Figure 22. It can use both data and query aggregation. The advantage of this protocol comes from energy efficiency when sinks are mobile: sink location updates are propagated within the local cell only and some of the grid nodes, not within the entire network.

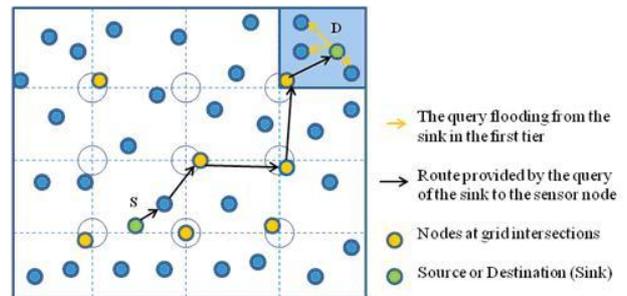


Figure 22. Two Tier query and data forwarding with the TTDD protocol

To add clarity to the above presented protocols, Table 3 classifies position-based routing protocols. The geographic protocols are divided into two categories: designed for actual routing and designed to improve the routing process and simulated in the original proposition articles with geographic routing. The non-geographic routing are divided here into topology based, meaning algorithms which use route discovery (reactively or proactively) and hierarchical. The table contains geographic routing protocols which can be considered as hierarchical as well and, in this case, they will be marked accordingly. The third category of the table presents some of the approaches of the protocols: some are designed for security, same to avoid beacon use, while others are based on 'distance, direction and progress', 'multipath or flooding' or for energy efficiency. The information provided in Table 3 is meant to add clarity to Section 3 and to the application suggestions made in Section 6 as well.

6. Application suggestions for position-based routing protocols

The following section describes possible application fields and their applications as well as their requirements on routing. By matching the application requirements to the characteristics of the position-based routing protocols described in the previous sections and tables, Table 4 has been produced.

According to the design issues of a network, some position-based routing protocols offer certain advantages over the others. Whether they are power efficient, guarantee delivery, scale well or are real-time algorithms and take into consideration realistic channels or sensors with power scavenging abilities, each presents a characteristic that would make the protocol more appropriate for a type of application. This depends on the quality of service demanded by the application and the differences between the protocols, as is explained in the following paragraphs.

There is a wide variety of applications which can be categorized as belonging to different areas such as industrial, home, health, environmental, military, automotive and commercial. The network challenges in each area are to some extent similar in the sense that all the routing protocols used in these network applications have to be as fault tolerant, as power efficient and low latency as possible and have to have a high delivery ratio. Also, the production costs of the network need to be kept low. If it is a sensor network, sensor node capabilities can influence node costs and eventually network production

costs. However, it is the network differences which recommend a specific routing protocol for a specific application. Applications differ through the required operating environment, quality of service, number of events to be detected or tracked and dynamism of the events.

Industrial applications can require networks to function in an in-door environment (factories, warehouses), attached to machinery or dispensed throughout the compound, or in an outdoor environment. Possible applications refer to monitoring and control of industrial equipment, processes and personnel. The QoS requirements are real-time communication and collaborative processing. Routing in such an environment can become especially difficult due to obstacles and noise which can affect the sensor nodes' line of sight communication. Node deployment is of great importance in these cases because this affects routing performance. Nodes can be manually placed in the case of industrial applications, in a deterministic way, and data can be routed on pre-determined paths. The manual deployment of nodes is not an impossible task in this case as the network size is probably of medium size. However, a pre-deterministic approach could be applied only in the case of static routing. If nodes have to be attached to limited-moving machinery, a solution would be to increase the transmission range of each node to have sufficient coverage on a limited area of mobility. As a result power and bandwidth consumption would increase, consequently affecting routing.

Home applications refer to in-door environments. Higher bandwidth might be necessary for gaming or entertainment purposes, but considering strictly sensor network applications, QoS requirements are reduced. Communication inside a home is safer, so less processing overhead is created by security needs and less energy is consumed. Home automation consists of sensor enabled appliances interconnected which communicate to a central control system [4]. Therefore, the size of the network is small due to the small number of events to be detected and tracked. Usually, there is also no movement involved in home sensor networks, so relatively static routing is recommended.

Health applications are defined here to be in hospitals and clinics, so inside buildings. Therefore they are in need of in-door routing for small or medium networks. Geographic routing may not be the best choice (as explained below). However, for tracking personnel and patients, sensor mobility is required. Position-based routing, when implemented in different protocols, offers mobility adaptation and can actually outperform other routing methods in mobile scenarios. Among routing requirements of health applications are: reliability, robust routing, high fault tolerance and high delivery ratio. Latency cannot be tolerated in routing when it comes to patients' lives. For example, if a heart attack is detected and signalled with delay, a human life might be jeopardized. Aggregation methods are not necessary and they cause latency. Energy constraints are the trade-off. If the network is positioned inside a building and not in a remote area, it is assumable that a power supply is available for battery recharging or sensors whose batteries fail can be recharged or replaced.

In medical applications, sensor nodes have to provide extra functions and are called smart sensors. They can be used on-body and off-body. On-body sensor networks are small in dimension and do not require geographic routing, but off-body applications may make use of position-based routing in certain cases. Sensor nodes for health applications in general have to be able to detect motion, so position, velocity, angular velocity and acceleration, and have to be able to detect personal features. In applications dedicated to monitoring patients' vital signs, sensors are necessary for the detection of the heart rate, temperature, blood pressure and blood oxygen level or for biochemical agents present in the blood stream. Fall detection, video surveillance, sleep disorder monitoring, heart attack identification, obesity problems, all require sensor networks. The collected data is stored, correlated and software management is necessary for issuing warnings in case of a threshold breach [72].

Industrial applications, home applications and some health applications have two main characteristics in common: they require static routing (or reduced mobility) and small to medium networks. Geographic routing, which is the most advantageous for sensor networks, uses geographic location which is not really appropriate for small, in-door networks. In a building of limited geographic area, the use of geographic coordinates doesn't make sense. However, position-based algorithms may be used, even without the need to be very scalable, because it is not really necessary for these networks to grow to a metropolitan size.

Environmental applications usually refer to network nodes distributed in certain fields (crops, forests, volcanoes, sea, air, space) and can be categorized as: physical world surveillance and emergency situation surveillance [4]. In both types of applications, networks have to be of medium to high size due to the number of events they may have to detect and track. In physical world surveillance, sensor networks can be used to track different parameters such as motion, sound, temperature, light, humidity, atmospheric pressure, etc. Their information is useful in tracking animal migration, climate change and the effects it has on crops, sea ice, snow and landslides. The possibilities are extremely numerous. In emergency situation surveillance, nodes may have to track natural catastrophes, detect hazardous chemical levels, fires, floods etc. and the information provided through on-site reports can be used for management, crisis response, disaster relief and emergency rescue operations.

The nature of the environmental application dictates the number of nodes, whether they are static or mobile and the required quality of service. Regarding this last feature, it can be said that the network's length of life is one of the most stringent needs for environmental applications. Geographic routing algorithms with long network life time should have increased energy efficiency as well. To achieve energy efficiency network routing has to have very little overhead and make use of data aggregation to eliminate communication redundancy. Also, the power consumption of nodes has to be minimal because of their reduced battery power. If the node deployment is in a remote location node replacement or battery charging can be difficult or even impossible. Another requirement is robustness of algorithms. If the routing algorithm cannot

reroute the message on a different path, node failure can cause routing failure. So robustness is also a recommended characteristic. As a difference between physical world surveillance and emergency situation surveillance, the latter has to be served by a routing protocol with very little latency and good data reliability, while the first type of surveillance is not as demanding on routing speed.

Military applications can refer to both indoor as well as outdoor networks. Ad-hoc networks are preferred to sensor networks because remotely deployed nodes with battery failure are difficult to access and replace [9]. However, if sensor networks are chosen, it is because of the properties sensor nodes have. So, combat field surveillance, recognition missions, remotely controlled landmines that are target specific, intrusion detection and criminal hunting [2] are just a few of the application possibilities. Networks used in military applications should be designed for the multiple intelligently performed tasks according to the applications' demands: surveillance, recognition, targeting, tracking and control. Geographic routing is recommended for outdoor military applications with large network implementations. The routing requirements for this area are similar to the environmental ones, but are more stringent regarding security and confidentiality [4], something that will reflect in processing overhead and energy consumption. Therefore energy efficiency demands have to be compensated through the elimination of other power consuming factors.

Automotive applications may refer to two subcategories: for in-car purposes such as Internet access or entertainment or for large scale, out-door networks implemented using vehicles as nodes. The applications can make use of both mobile wireless sensor networks as well as mobile ad-hoc networks. A new type of network was considered in the '80s, based on ad-hoc networks, and is now possible: VANETs (vehicular ad-hoc networks). The interest in this type of application comes from the mobility of the nodes which are fitted on vehicles and communicate through wireless technology. The applications can be multiple and all can make use of local information propagation. VANETs can be used for the extension of the wireless range of base stations, for traffic decongestion in busy areas, for driving assistance when supplementary information is needed about local gas stations, parking spaces, shops and restaurants, for driving safety when the weather changes or for avoiding accident areas. The size of such a network can reach metropolitan areas and the routing could take place by using both mobile as well as static vehicles. However, the disadvantages would be the speed and unpredictable directions of vehicles leading to connectivity issues [73]. Referring to dynamic topologies, geographic routing is superior in performance to other routing schemes. This is why it is recommended for automotive applications. The requirements of such applications on routing are robustness, high speed, precise localization, good coverage and high fault tolerance.

Commercial applications refer to small indoor networks used in conferences and meetings, or to larger outdoor mesh networks or extensions to services provided by cellular infrastructure [9]. Commercial applications can use ad-hoc networks instead of wireless sensor networks because of their less demanding characteristics. Two such examples

of static ad-hoc networks are given in [5]: Metricom Ricochet and Nokia Rooftop systems. For conference applications, the routing protocol has to consider a realistic lossy wireless channel and real time message delivery without delays and latency. Fault tolerance and high delivery ratio are primary requirements because the final purpose of the application is to assure communication. Mobility is not really applied in these applications, but for mesh networks and cellular infrastructure, mobility can imply robust routing requirements.

Table 4 offers suggestions of suitable protocols for certain applications based on the characterization of each area of application and of each protocol. The table contains columns which mention the application area, possible applications, their requirements and the protocols with their general network characteristics.

7. Future research

Although geographic routing has been a well studied subject in the last decade, there are still many research directions to investigate. Here are a few which aim to enhance the practicality of this type of routing:

Resilience to location errors. Position based algorithms have to consider the intrinsic error of inaccurate localization techniques. Analyzing the impact that existing positioning systems have on the routing behavior can shed light on the degree of degradation which unrealistic settings lead to. Geographic routing can be improved by incorporating the error probability in routing decisions. Making routing robust to errors requires knowledge about the level of accuracy and the strains localization methods inflict on network as resources power consumption and connectivity.

Mobility adaptation. Network applications may require quality routing in highly dynamic environments. Vehicular or aeronautical ad-hoc networks have already been studied and many protocols have attempted to provide solutions for quality of services in mobile networks, but compromising energy efficiency and memory resources for better throughput makes geographic routing lose its edge over other algorithms. More practical solutions are needed which maintain energy consumption low and preserve the packet delivery ratio even when nodes are mobile.

3D applicability. Existing algorithms are designed for 2D topologies and their techniques are not applicable in 3D graphs. New issues arise when 3D networks are implemented because: node density has to be increased for similar network coverage, algorithms for recovery from local minimum have to be reconsidered, behavior in the face of localization errors is no longer the same and theoretical studies with assumptions of a unit ball graph (UBG) have poor practical performance because of imperfect radio ranges between nodes.

Secure routing. Security is an issue of major concern in military applications especially, but most position based routing protocols have not been fully developed to the extent to which this aspect is fully investigated and incorporated.

Most of the solutions provided so far by geographic routing proposals promise a lot, but are sometimes theoretic in nature and have simplified assumptions on link reliability

and radio transmission. Algorithms can be more application-driven by considering the above research directions.

8. Conclusions

The need to design efficient, scalable protocols makes position-based routing and especially geographic routing attractive. The latter facilitates stateless, energy efficient, scalable routing which both ad-hoc and especially sensor networks can make use of. The number of applications that can benefit from efficient routing is impressive and, as a consequence, numerous location-based routing protocols have been developed to better accomplish the routing process according to the application demands. However, since position-based routing methods also have a few intrinsic disadvantages which are still under research (such as imperfect localization), their advantages are disregarded and the protocols presented in this paper have not been implemented. Since an aim of network development is to provide application generic solutions, their suitability for particular application groups has been discussed.

Over viewing the existing position-based routing protocols and selecting one for a specific application, can be an intimidating task for anyone. Due to the number of existing possibilities and the fact that each protocol has a certain trade-off, geographic routing might be neglected as an option for the newly designed sensor network. To avoid this from happening, this article proposed to simplify the selection process of a routing protocol. The surveyed material is intended as an aid in the difficult protocol comparison and selection task. The starting points of an analysis are the particular characteristics of the application area and of the application, as described in Section 5. Once the size of the desired network and the environment where it should be set up is established, the focus can move to the most stringent demands of the application and on the desired quality of service. The protocol choices can therefore be narrowed down to just a few potential candidates from the already investigated position-based routing protocols in Tables 2a-f.

Appendix 1 presents important position-based algorithms for both ad-hoc and wireless sensor networks, in both static and mobile scenarios. Their total number is impressive and their novelty and success represents the continuous efforts of the research community to meet with the stringent needs of modern, challenging networks. The presented protocols propose different solutions and trade-offs and their design successfully answers only some of the requirements of volatile, demanding networks. Thus they are suitable for certain applications only, where chosen characteristics are valued above others. Application suggestions have been made according to the features relevant for each group of applications.

As a result of the comparison made in Table 2a-d, it can be concluded that there are some generic characteristics a position-based routing algorithm must have. Taking as an example the mobility aspect, one can consider either a static or a mobile network. In the static case, the routing protocol will not suffer from delays or latency, since there are no updates to be made, and the resources should therefore be focused in the direction of efficient packet delivery or real time communication.

Because mobility results in extra energy consumption spent on updates and processing of location information, a reliable mobile protocol should focus more on energy consumption issues, of course without ignoring speed or delivery efficiency. However, in most cases there is a trade-off between these factors.

Choosing a position-based routing protocol ultimately results in making a compromise between certain stringent features and others with lower priority. A lot of attention has to be given in the design of a network (be it a sensor or an ad-hoc one) to the details listed in the protocol tables referenced in Section 5. Without an efficient protocol for the specific application, the communication goal of the network may not be fully accomplished. The short life time of sensor nodes and the failure to deliver the minimum amount of transmitted packets in a desired amount of time can be translated into the design of an unsuccessful network and the waste of time and resources.

The initial assumptions in the design of a position-based protocol must also be carefully considered. Assumptions made about network density, which is sometimes considered high enough to prevent the existence of communication voids, can lead to a faulty routing behaviour in a sparse network. Also, increasing the density above a certain threshold may not be beneficial to the localization process as shown in [74]. When designing a network and choosing a routing protocol, assumptions about precise localization or the employment of expensive GPS devices in all nodes can lead to either inefficient routing or increased cost. Also, lack of connectivity or insufficient consideration of weak links can severely affect routing in real time networks, through congestion, end-to-end delay and packet failure. Energy efficiency or the energy harvesting capabilities of sensor nodes also need investigation.

Written with the intention to shed light on existing geographic routing possibilities and to help in the design process of ad-hoc and sensor networks, this survey suggests which protocols are most suitable for certain applications. It also helps in understanding the steps made in the design of position-based routing protocols for highly demanding network applications and which aspects still require a lot of attention. While some protocols guarantee delivery, have excellent delivery ratio, look promising from the mobility point of view or seem satisfactory regarding memory availability, they still need a lot of improvement in other areas. Geographic routing also leaves room for further research and progress, but its benefits for future network design look very promising.

Appendix 1: Protocol Comparison Tables

Table II a. Comparison of Geographic Routing Protocols

Protocol	Loop freedom	Distributed operation	Path strategy	Forwarding method (Forwarding is abbreviated f.)	Path selection metric	Memory	Guaranteed delivery	Scalability(network restrictions)
MFR, DIR	Yes/No	Localized	Single path	Greedy	Hop count	No	No	High/Medium
FACE, GFG	Yes	Localized	Single path	Greedy/Greedy & Face	Hop count	No	Yes	High
GEAR, EEFS	Depend./-	Localized	Single path	RGF or RDF/ Distance & power based	Power (residual energy)/ Cost: PRR x d	Yes	No (95% for uniform traffic)/No (if no ARQ)	Medium (GEAR-dense, EEFS-static)
V-GEDIR & GEDIR-2, f- & 2f-GEDIR	Yes	Localized	Single path/ Single path & multipath	Greedy/ Greedy & flooding	Hop count	Yes	No (over 90%)/ Yes (100% - static, over 94% -mobile)	Low - for basic Medium - for hybrid (dense)
GRWLI	-	Localized	Single path	Greedy	Hop count	Yes	No	Medium
GPSR,SPEED	Yes	Localized	Single path	Greedy & Face/ Greedy	Hop count	No	No (over 94%)/No	Medium (GPSR-dense)
GOAFR	Yes	Localized	Single path	Greedy & Face	Hop count	No	Yes	High
CBF	-	Localized	Single path	Greedy	Hop count	No	No	High
IGF, BGR	-	Localized	Single path	Based on distance, remaining node energy & random delay/ Based on distance to destination & contention time	Hop count	No	No (occasionally 100%)/No	Medium (dense)
ARRIVE	Yes	Localized	Single path	Greedy (Based on Probability)	Bandwidth, Power & distance-to-destination	Yes	No	Medium (dense)
LED	No	Localized	Single path	Greedy (Based on Probability)	Power & Distance	No	No	High
EGR, AeroRP	No/-	Localized	Single path/ Single path	Greedy & Recovery (modified perimeter)/Greedy	Hop count & Residual Energy/ Hop-count (TTI)	Yes/No	No	Medium (density)
EEGR	Yes	Centralized	Single path	-	Arc cost	Yes	No (100% in dense)	Medium
I-PBBLR	Yes	Localized	Single path	Greedy	Progress & direction	No	No	High
GREES (-L and -M)	-	Localized	Single Path	Based on packet advancement, residual battery & energy supply	Power (2 cost metrics)	Yes/No	Yes (MAC ACKs)	Medium (dense)
EBGR	Yes	Localized	Single Path	Greedy & Recovery	Power and distance	No	Yes	High
EAGPR, ORF&OFEB	-	Localized	Single path	Greedy	Power & Distance/ Hop count	Yes/No	No	High

Table II b. Comparison of algorithms designed to improve geographic routing

Protocol	Loop freedom	Distributed operation	Path strategy	Forwarding method (Forwarding is abbreviated f.)	Path selection metric	Memory	Guaranteed delivery	Scalability (network restrictions)
GLS (GRID)	-	Localized	Single path	Hierarchical strategy	Hop count	-	No	Medium
MECN, SMECN	Depend.	Localized	Single path	Depend. on the routing algorithm	Power	No	Depend.	Depend.
SPAN	-	Localized	Single path	Greedy	Hop count	Yes	No (90%)	High
TBF	Yes	Localized	Single path	Hybrid: Source based & Cartesian f.	Distance to trajectory	No	-	Medium
LOSR	Yes	Localized	Single path	Greedy & Face	Power Metric	Yes	No (almost 100% for dense)	Medium

Table II c. Comparison of Topology Based Protocols

Protocol	Loop freedom	Distributed operation	Path strategy	Forwarding method (Forwarding is abbreviated)	Path selection metric	Memory	Guaranteed delivery	Scalability (network restrictions)
LAR	No	Localized	Multipath	RDF	Hop count	Yes	No	Medium
DREAM	No	Localized	Multipath	RDF	Hop count	Yes	No (80%-basic)	Medium
GRUPI	Yes	Localized	Single path	Greedy & Flooding	Hop count	Yes	Yes	High
SPAAR	Not malicious	Localized	Single path	RDF – for route discovery	Distance	Yes	-	Medium
ALARM	No	Localized	-	RDF & box flooding	Link duration	Yes	No (80%)	High
BLR	-	Localized	Single path	Greedy with shortest f. delays and partial flooding for route request	Hop count	No	No	Medium (BLR-dense, to large ranges)
DSAP, MDSAP	-	Localized	Single path	Directional f.	Directional value & power/ Hop count	No/-	-/ Yes	-(topology)/Yes
SWING, SWING+	-/Yes	Localized	Single path	Greedy with route discovery/Greedy	Hop count	Yes	Yes	Medium/Medium(sparse)
AODPR	-	Localized	Single path	RDF - for route discovery	Distance	Yes	-	Medium
MACQP	Yes	Localized	Multipath	Greedy (Based on Probability)	Hop count	Yes	No	Medium (density)
RGRP	No	Localized	Single path	Greedy with route discovery	Hop count	No	No	High

Table II d. Comparison of Hierarchical Protocols

Protocol	Loop freedom	Distributed operation	Path strategy	Forwarding method (Forwarding is abbreviated f.)	Path selection metric	Memory	Guaranteed delivery	Scalability (network restrictions)
TMNR	Yes	Localized	Multipath	Based on distance vectors & anchored paths	Hop count	Yes	Yes	High
GAF (-b, -ma)	Depend.	Depend.	Depend.	Depend.	Depend.	Depend.	No (85%-99%)	Medium (dense, topography and range)
LABAR	-	Zonal	Single path	Directional routing	Hop count, distance	Yes	-	High
TTDD	-	Localized	Single path	Greedy for grid formation & local flooding for queries and dead ends	Hop count	No	No (over80%)	High

Table II e. Comparison of Protocols which are adaptive to mobility

Protocol	Overhead		Additional Information		
	Packet overhead	Processing overhead	Network type	Network Recommendations (size/density/mobility/node distribution)	Transmission type
MFR	Low	Low	MANET	Random Uniform	N2N unicast
LAR	Medium	Low	MANET	Small/Medium/Static	N2N unicast
DREAM	Medium	Low	MANET	Small/Medium/Mobile	N2N unicast
MECN	Medium	Low	MANET/ mobile WSN	Better for static	S2N anycast; N2S multicast
SMECN	High	Low	MANET/ mobile WSN	Large/Static and presumably mobile	N2S anycast; S2N multipath periodic broadcast
TMNR	Medium	Low	MANET	Large/Highly mobile	N2Nunicast
GLS	Low	Low	VANET	Medium size	N2N unicast
GPSR	High	Low	MANET/WSN	Dense	N2N unicast
GAF (-b, -ma)	Medium	Low	MANET/ WSN	Dense/Static/Mobile (GAF-b for low mobility, GAF-ma for high mobility)	N2N one hop broadcast
GRUPI	Medium – for static	Low – for static	Ad-hoc	Large/Static, but can be adapted for mobility	N2N unicast, broadcasts
SPAAR	High	High	MANET	For high risk, tactical net. or managed-hostile environments	N2N unicast, broadcast
CBF	High	Low	MANET	Dense	N2N unicast, broadcast

GRWLI	Medium	Low	Ad-hoc/WSN	Dense/Static	N2N unicast, periodic broadcast
TBF	Medium	Depend.	MANET	Dense/Static WSN (static sinks)	N2N unicast
ALARM	Medium/High	Low	MANET & WSN	Mobile	N2N unicast, broadcast
BLR	Medium	Medium	MANET	Dense/ Static and Mobile	N2N unicast, broadcast
TTDD	Medium	Medium	WSN	Large/ For mobile sinks & static sensors	N2N unicast, broadcast
LOSR	High	Low	WSN	Large/Dense	unicast
SWING+	High	Low	MANET	Small-Medium/Static or Mobile	N2N unicast
MDSAP	Medium	Medium	WSN	Large/Static or mobile WSNs	N2N unicast
GEDIR	Low	Low	WSN	Basic Alg. – for Dense/Static; Hybrid Alg. – for Dense/Static & Mobile	N2N unicast
IGF	Medium	Low	WSN	Dense/Static & Mobil	N2N unicast broadcast
I-PBBLR	Low	Low	MANET	For mobile/sparse net.	N2N unicast broadcast
SPAN	High	Medium	Ad-hoc	Dense/Static/Mobile ad-hoc	N2N unicast, broadcast
AeroRP	Medium	Low	WSN	Large/Dense/Mobile	N2N unicast broadcast
EGR	Medium	Low	Ad-hoc	Mobile/Random	N2N unicast broadcast
EBGR	Low	Low	WSN	-	N2N unicast broadcast

Table II f. Comparison of protocols which are not adaptive to mobility

Protocol	Overhead		Additional Information		
	Packet overhead	Processing overhead	Network type	Network Recommendations (size/density/mobility)	Transmission type
SPEED	High	Low	WSN	For real-time communication	N2N unicast, area-anycast, area-multicast
GOAFR	Low	Low	Geometric Ad-hoc n.	Sparse/Static	N2N unicast
ARRIVE	Medium	Medium	WSN	Dense WSN, in highly volatile environments	N2N unicast, broadcast
BGR	Low	Low	WSN	Dense	N2N broadcast
SWING	Medium	Low	MANET	Static	N2N unicast
AODPR	Medium	High	MANET	Any node density	N2N unicast
DSAP	Low	Low	WSN	Static/Fixed topology	N2N unicast
EEGR	Medium	Low	WSN	Dense/Static WSN	N2N unicast, broadcast
EEFS	Low	Medium	WSN	Low-rate/time-scheduled/Static/uniformly distributed	N2N unicast
GREES (-L & -M)	High	Low	WSN	Uniformly distributed/Dense	N2N and N2S unicast, broadcast
GEAR	Medium	Low	WSN	Dense/Static	N2N unicast, broadcast
LABAR	Low	Low	Ad-hoc networks	Large WSN and ad-hoc networks.	N2N unicast, broadcast for G-nodes
MACQP	Medium	Medium	WSN	On clustered large static n.	N2N unicast
LED	Low	Low	Ad-hoc & WSN	Large/Dense/Static random uniform topology	N2N unicast
EAGPR	Low	Low	WSN	Medium/Static/Random	N2N unicast
ORF&OFEB	Low	Low	Ad-hoc	Static	N2N unicast
RGRP	Low	Low	WSN	Static	broadcast N2N unicast

Table III. Classification of geographic and non-geographic protocols and some of their approach

Protocol	Geographic algorithms		Non-Geographic algorithms		Design Approach Characteristics			
	For Routing	To support Routing	Topology-based (with route discovery)	Hierarchical	Security	Beacon-less routing	Distance, direction and progress	Energy efficiency
MFR	✓						✓	
LAR			✓	✓				
DREAM			✓					
GFG	✓							
FACE	✓							
DIR	✓						✓	
MECN		✓						✓
TMNR			✓	✓				
GLS		✓		✓				
GPSR	✓							
SMECN		✓						✓
GRUPI			✓				✓	
GEDIR	✓						✓	
GEAR	✓							✓
GAF				✓				✓
SPAN		✓		✓				✓
SPAAR			✓		✓		✓	
SPEED	✓							
GOAFR	✓							
LABAR			✓	✓			✓	
CBF	✓					✓	✓	
IGF	✓					✓		✓
GRWLI	✓							
ARRIVE	✓				✓		✓	
TBF		✓					✓	
ALARM			✓				✓	
BLR			✓			✓		✓
DSAP			✓				✓	✓
EEFS	✓						✓	✓
TTDD			✓	✓				
I-PBBLR	✓					✓	✓	
BGR	✓					✓	✓	✓
SWING			✓					
AODPR			✓		✓		✓	
LOSR		✓						✓
GREES	✓							✓
SWING+			✓	✓				
EEGR	✓							✓
MDSAP			✓				✓	✓
MACQP			✓	✓				✓
LED	✓						✓	✓
EGR	✓							✓
ORF&OFEB	✓							✓
RGRP			✓					
EBGR	✓					✓	✓	✓
EAGPR	✓						✓	✓
AeroRP	✓							

Appendix2: Application Suggestions

Table IV. Application suggestions for position-based routing protocols

Area	General applications		Requirements	Protocols – Network Characteristics	
Industry	Monitoring and control of industrial equipment, processes and personal		<ul style="list-style-type: none"> -medium scalability -indoor performance -static or reduced mobility -real-time communication -realistic channel implementation -GPS-equipment not necessary (nor geographic localization) -relaxed energy requirements -good delivery -medium security 	SWING – relatively static DREAM – small/medium/mobile, no guaranteed delivery TMNR – large/very mobile, guaranteed delivery ALARM – large, static (preferably static) or mobile, no guaranteed delivery BGR –large, dense, static CBF – large, mobile IGF – large, static or mobile LABAR –large, static	
Home	Home automation		<ul style="list-style-type: none"> -little-to-medium scalability -indoor performance -static nodes -realistic channel implementation for indoor use -relaxed message delivery - GPS-equipment not necessary (nor geographic localization) - relaxed energy requirements - good delivery -no security 	GEAR – for aware home project[3], SWING – relatively static LAR – small/medium/static, no guaranteed delivery DREAM – small/medium/mobile networks which do not require guaranteed delivery GOAFR – low density/static, guaranteed delivery SPEED – real time communication, medium size, static, no guaranteed delivery	
Health	Monitoring and measuring parameters from sensors		<ul style="list-style-type: none"> -little-to-medium scalability -static or mobile nodes -robustness against node and delivery failure -small-to-zero delay and latency -relaxed energy constraints, depending on the situation -GPS-equipment not necessary (nor geographic localization) -no security 	SPEED – vital sign project MDSAP – recommended for a medical application by author GEDIR – small/static, guaranteed delivery GRUPI– large, mobile, guaranteed delivery	
	Monitoring personnel and patients (locations & health condition)				
Environment	Physical world surveillance	Parameter monitoring in different situations	<ul style="list-style-type: none"> -high scalability -outdoor performance -static or mobile nodes -high energy efficiency -long lifetime -good network coverage -use of aggregation for little redundancy - good delivery -no security 	SPAN & GAF - habitat monitoring-great duck project [75], GEAR, GREES – especially for physical world surveillance ARRIVE – for environmental monitoring and distributed control; EEFS – recommended for low rate, no interference, time scheduled applications SPEED – in emergency situations because of real-time communication, medium sized, static, no guaranteed delivery SPAAR – recommended by author for emergency responses in disaster areas MECN – can be used in a multi-sensor network with a single station for supervision LAR, DREAM – small/medium, no guaranteed delivery (parameter monitoring) TMNR – large/mobile, guaranteed delivery: for crisis response, disaster relief, emergency operations GEDIR – small/static networks, guaranteed delivery (parameter monitoring, hazard detection) GOAFR – low density/static, guaranteed delivery ALARM –large, static (preferably static) or mobile networks, no guaranteed delivery TBF – dense, static networks without security BGR – large, dense, static BLR – large, dense, static and mobile CBF –large, mobile AeroRP – for aerodynamic networks	
		Tracking animal migration			
		Tracking climate change and the effects it has on crops, sea ice, snow and landslides			
	Emergency situation surveillance	Track natural catastrophes			<ul style="list-style-type: none"> -high scalability -indoor, mostly outdoor performance -mostly static nodes -high energy efficiency -long lifetime -good network coverage -speed for emergency -use of aggregation for little redundancy -medium security
		Detect hazardous chemical levels			
		Detect fires			
		Detect floods			
	Crisis response				
	Disaster relief				
	Emergency rescue				
Military	Combat field surveillance		<ul style="list-style-type: none"> -high scalability -indoor and mostly outdoor performance -high energy efficiency -long lifetime -good network coverage -high speed (little-to-no latency or delay in message delivery) - adaptive to mobility -use of aggregation for little redundancy -high security -guaranteed delivery 	GAF – object tracking project[3] TTDD – suggested by author for tank detection, SPAAR – recommended by author for military applications in a high -risk battle environment, security oriented MECN, SMECN – for digital battlefields GRUPI– large, mobile networks, guaranteed delivery, no security AODPR – for large networks, with any node density and security against target-oriented attacks ARRIVE – security AeroRP – for aerodynamic networks	
	Recognition missions				
	Remotely controlled landmines				
	Intrusion detection				
	Criminal hunting				

Automotive	As extension of the wireless range of base stations	-high scalability - outdoor performance -well adaptive to high mobility -high energy efficiency -long lifetime -good network coverage and connectivity -high speed in message delivery -good fault tolerance -good localization -high security -guaranteed delivery	GLS(GRID)-VANET GPSR [75] TMNR –large/very mobile, with guaranteed delivery LOSR – large, dense mobile, no guaranteed delivery GRUPI – large, mobile, guaranteed delivery AeroRP – for aerodynamic networks (could be used for land vehicles as well)
	For traffic decongestion in busy areas		
	For driving assistance when supplementary information is needed about local gas stations, parking spaces, shops and restaurants		
	For driving safety when the weather changes		
	For avoiding accident areas		
Commerce	Conferences	-static (mostly) and mobile -low scalability and indoor performance or high scalability and outdoor performance -long lifetime -real-time communication -realistic channel implementation -good speed in message -guaranteed delivery	MECN – can be used for a cellular phone system which requires a longer network life SMECN – (less complex, more power efficient, more realistic), but simulated scenario is not recommended for Internet and telephone networks GRUPI – can be used for Internet routing SPEED – real time communication, medium sized, static, no guaranteed delivery
	Meetings		
	Extension to cellular networks		

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