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To me and to whom who believes in me

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Abstract

The advances in mobile robotics allow us nowadays to include the mobility perception into various and different classes of WSNs. Indeed, the use of mobile sensors is possible and useful in many application scenarios, ranging from environmental monitoring and public safety applications, to the industry, healthcare and military applications. However, introducing mobility to the nodes causes a dynamic topology in mobile wireless sensor networks (MWSNs) which causes challenges for routing protocols, since there is no fixed path from source to destination (sink). Thus, the process of routing in a MWSN necessitates alternative solutions to those designed for static WSNs or MANETs.

In his thesis, we address the problem of routing in MWSNs with a special attention to geographic routing and its challenges. A state of the art of geographic routing in MWSNs is investigated and a number of routing protocols especially designed for MWSNs are reviewed following a new taxonomy. In this review, we have surveyed more than twenty geographic protocols and classified them into two main categories: *Protocols supporting mobility* and protocols that consider *localization errors* in routing decisions since sensors cannot always get accurate positions. From this survey, we concluded that non consideration of nodal mobility and location errors can affect considerably the geographic routing performance and may lead to transmission failures.

Geographic routing protocols with mobile sinks have been proposed in order to respond to specific applications as well as for improving the network lifetime and reducing the transmission delays. Our first contribution was to propose a geographic routing called *M-Elastic* that supports more characteristics related to the mobility of sinks and cope with its side effects. Improvements were done to support the multiplicity of mobile sinks, the temporary absence of the sink, higher speeds and different trajectories of the mobile sink. Results reveal that with multiple mobile sinks, M-Elastic gives better results in terms of success delivery ratio. In case of sink's absence, M-Elastic saves up to 25% of packets from being dropped and important packets will be sent according to their priorities. Finally, predicting the location of the mobile sink improves the delivery ratio and reduces the delivery delay.

Geographic routing in MWSNs requires the knowledge of nodes' locations. However, localizing continuously mobile sensors is a very challenging problem that did not receive enough research. Part of our contributions, is the proposition of GPS-less localization methods to localize mobile sensors namely *MA-SDPL (Multi-Anchors SDPL)* proposed when having the possibility of deploying multiple anchors and *MH-SDPL (Multi-hop SDPL)* proposed when applying a multi-hop localization to assist the unique mobile anchor. The proposed methods can be considered as improvements of the method SDPL (Speed and Direction Prediction-based Localization) in terms of coverage, consumed energy and localization error. From simulation results, with *MA-SDPL*, the localization error was reduced considerably and with MH-SDPL, the energy resources were optimized. Overall, the results are promising and these localization methods can be a preliminary phase for any geographic routing in MWSNs.

Most of localization methods give only estimations and errors are inevitable. Without considering these location errors in geographic routing, routing decisions can be totally erroneous thus leading to a high rate of packet loss. In addition, the mobility of nodes can cause intermittent connectivity that affects significantly the communication characteristics in a network. In this thesis, we propose also INTEGER, a new error resilient geographic routing intertwined with a localization method specifically designed for mobile sensor networks under more realistic assumptions and even when these networks are intermittently connected. By combining the localization with a mobility adaptive geographic routing process, INTEGER selects efficiently relay nodes based on nodes' mobility predictions and makes significant progress towards the destination. To our knowledge, INTEGER is the first protocol that tackles localization and geographic routing for intermittently connected mobile sensor networks at the same time. The routing algorithm is composed of two main components namely the on-demand mobility-based adaptive neighborhood discovery and the best forwarder selection. Results show that INTEGER improves the efficiency of the routing by increasing the packet delivery ratio and by reducing the energy consumption while minimizing the number of relay nodes. Protocols supporting intermittent connections are often delay tolerant due to the time necessary to reach the sparse regions of the network. Based on that, we further compared INTEGER with concurrent delay tolerant protocols. Results showed that INTEGER outperforms its competitors by handling efficiently the local maximum problem while reducing the end-to-end delay and increasing the packet delivery.

Key Words: *Geographic routing, Localization, Location errors, Mobility management, Delay-tolerant networks, Mobile Wireless Sensor Networks*

Résumé

Les progrès de la robotique mobile nous permettent aujourd'hui d'inclure la perception de la mobilité dans différentes classes de réseaux de capteurs sans fil (WSNs). En effet, l’utilisation de capteurs mobiles est possible et utile dans de nombreux scénarios et applications, allant de la surveillance de l’environnement et de la sécurité publique aux applications industrielles, de santé et militaires. Cependant, l'introduction de la mobilité aux nœuds crée une topologie dynamique pour les réseaux de capteurs sans fil mobiles (MWSN), ce qui représente un défit pour les protocoles de routage, en raison de l’absence d’un chemin fixe entre la source et la destination (sink). Ainsi, le processus de routage dans un MWSN nécessite des solutions alternatives à celles conçues pour les WSNs statiques ou les MANETs.

Dans sa thèse, nous abordons le problème du routage dans les réseaux de capteurs sans fil mobiles (MWSNs) en portant une attention particulière au routage géographique et à ses défis. En effet, la nécessité de concevoir des protocoles efficaces et évolutifs rend le routage géographique très attrayant, car il peut fonctionner avec moins de mémoire, il est économe en énergie et est évolutif, en particulier pour les réseaux mobiles caractérisés par de fréquents changements de topologie où le routage géographique a une réponse rapide et peut trouver rapidement de nouveaux itinéraires en utilisant uniquement les informations de topologie locale. Une étude bibliographique sur le routage géographique dans les MWSNs où des protocoles de routage spécialement conçus pour les MWSNs ont été examinés selon une nouvelle taxonomie. Dans cette étude, nous avons interrogé plus de vingt protocoles géographiques et nous les avons classés en deux catégories principales: Protocoles considérant *la mobilité*, et les protocoles qui prennent en compte *les erreurs de localisation* dans les décisions de routage du fait que les capteurs ne peuvent pas toujours obtenir des positions précises. Cette étude nous a permis de conclure que la non prise en compte de la mobilité des nœuds et leurs erreurs de localisation peut affecter considérablement les performances du routage géographique et entraîner des défaillances de transmission.

Des protocoles de routage géographique avec des sinks mobiles ont été proposés afin de répondre à des applications spécifiques, d'améliorer la durée de vie du réseau et de réduire les délais de transmission. Notre première contribution a été de proposer un routage géographique appelé M-Elastic qui prend en charge davantage de caractéristiques liées à la mobilité des sinks et qui fait face à ses effets secondaires. Des améliorations ont été apportées pour prendre en charge la multiplicité des sinks mobiles, l'absence temporaire du sink, des vitesses élevées et variées et trajectoires différentes du sink mobile. Les résultats révèlent qu’avec plusieurs sinks mobiles, M-Elastic donne de meilleurs résultats en termes de taux de délivrance des paquets. En cas d’absence de sink, M-Elastic économise jusqu’à 25% des pertes des paquets et des messages importants sont envoyés en fonction de leurs priorités après la disponibilité du sink. Enfin, la prédiction de la position du sink mobile permet d’améliorer le taux de délivrance et de réduire le délai de livraison.

Le routage géographique dans les MWSNs nécessite la connaissance des positions des nœuds. Cependant, la localisation continue des capteurs mobiles est un problème très complexe qui n’a pas fait l’objet de suffisamment de recherches. Une partie de nos contributions consiste en la proposition des méthodes de localisation sans GPS pour localiser les capteurs mobiles Ces méthodes proposées peuvent être considérées comme des améliorations de la méthode SDPL (Localisation basée sur la prédiction de vitesse et de direction) en termes de couverture, d'énergie consommée et d'erreur de localisation. L'extension appelée *MA-SDPL* (SDPL multi-ancres) a permis de réduire considérablement l'erreur de localisation. Dans le cas où plusieurs ancres ne sont pas disponibles, nous avons proposé MH-SDPL (Multi-hop SDPL) qui fonctionne avec le principe de localisation multi-sauts pour assister l'unique ancre mobile. Les résultats sont prometteurs et ces méthodes de localisation peuvent constituer une phase préliminaire pour tout routage géographique dans les MWSNs.

La plupart des méthodes de localisation ne donnent que des estimations et les erreurs sont inévitables. Sans tenir compte de ces erreurs de localisation dans le routage géographique, les décisions de routage peuvent être totalement erronées, entraînant ainsi un taux élevé de perte de paquets. De plus, la mobilité des nœuds peut entraîner une connectivité intermittente qui affecte considérablement les caractéristiques de communication dans un réseau. Dans cette thèse, notre troisième contribution principale est INTEGER, un nouveau schéma de routage géographique tolérant aux erreurs de positionnement entrelacé avec un algorithme de localisation spécialement conçus pour les réseaux de capteurs sans fil mobiles en considérant des hypothèses réalistes et même lorsque ces réseaux sont connectés par intermittence. En associant la localisation à un processus de routage géographique adaptatif la mobilité, INTEGER permet de sélectionner efficacement les nœuds relais en se basant sur la prédiction de la mobilité des nœuds et réaliser des progrès significatifs vers la destination. À notre connaissance, INTEGER est le premier protocole qui aborde simultanément la localisation et le routage géographique pour les réseaux de capteurs mobiles connectés de manière intermittente. L'algorithme de routage est composé de deux phases principales, à savoir la découverte à la demande du voisinage et adaptative à la mobilité et la sélection du meilleur relai. Les résultats montrent qu'INTEGER améliore l'efficacité du routage en augmentant le taux de délivrance des paquets et en réduisant la consommation d'énergie tout en minimisant le nombre de nœuds relais. Les protocoles prenant en charge les connexions intermittentes sont souvent tolérants au délai en raison du temps nécessaire pour atteindre les régions clairsemées du réseau. Sur cette base, nous avons comparé INTEGER avec des protocoles concurrents tolérants au délai. Les résultats ont montré qu'INTEGER surpasse ses concurrents en traitant efficacement le problème local maximum tout en réduisant le délai de transmission de bout en bout et en augmentant la délivrance de paquets.

Mots Clés : *Routage Géographique, Localisation, Erreurs de localisation, Gestion de la Mobilité, Réseaux tolérants aux délais, Réseaux de Capteurs sans fil Mobiles.*

List of Publications

International Journals

I. Benkhelifa, S. Moussaoui and I. Demirkol. (Oct. 2018). “Intertwined Localization and Error-resilient Geographic Routing for Mobile Wireless Sensor Networks”. In Journal of Wireless Networks. Springer. 2018. IF: 1.98. DOI: https://doi.org/10.1007/s11276-018-1836-7

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I. Benkhelifa, C. Lamini, H. Azouz and S. Moussaoui. (December 2016). "Prediction-based Localization for Mobile Wireless Sensor Networks". In Revue de l'Information Scientifique et Technique. Volume 22, Number 1, pp. 9-15.

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GENERAL INTRODUCTION

In the era of Internet of Things (IoT), a growing interest is recently addressed to mobile wireless sensor networks (MWSNs) by the industry and the research community. Indeed, MWSNs can play a vital role in today's real world applications in which sensor nodes are mobile. In fact, MWSNs are much more versatile than static sensor networks as they can be deployed in any scenario and cope with the rapid topology changes. The applications of MWSNs are numerous and range from economics, environmental monitoring, meteorology, healthcare applications, smart spaces and smart cities, traffic monitoring, search and rescue applications, tactical military surveillance, wild animal monitoring, underwater surveillance to name just a few.

Mobility can be introduced in three ways; the simpler is to have static sensors while sinks are the ones moving. The second approach is to maintain sinks static while sensor nodes are mobile. Finally, both approaches can be combined letting all nodes in the network be mobile. Mobility can be achieved by equipping nodes with mobilizers or by attaching them to mobile elements or vehicles. Sometimes, nodes displace due to some natural effects such as wind, ocean, animals, etc. therefore, mobility of nodes can be controllable, predictable, or totally random. However, the mobility of nodes adds more challenges such as the need for continuous localization, the management of the power consumption due the energy expenditure by the mobile nodes having self-mobilizers. In addition, routing in such dynamic topology represents a real challenge for MWSNs where finding an efficient route to a mobile destination or forwarding data through mobile relay nodes is not an easy task.

Currently, there is no standard for MWSNs. Often, protocols from MANETs (Mobile Ad Hoc Networks) are borrowed as they are able to work in mobile environments but they are designed for two-way communications, which is in sensor networks not required. Whereas, WSNs protocols often are not suitable, as they cannot handle the high frequency of topology changes. Geographic routing is recently gaining much attention from the research community due to its numerous advantages and suitability for MWSNs. Its simplicity and stateless nature make it very attractive since forwarding decisions are made locally and nodes need only geographic information of their direct neighbors. It is also energy efficient, in fact, such routing conserve energy and bandwidth since discovery floods and state propagation are not required beyond a single hop. Geographic routing has also fast response and can find new routes quickly by using only local topology information; this reduces the overhead required by other routing types for maintaining routing tables up to date in highly mobile scenarios. Scalability and autonomy are other attractive features of geographic routing. Motivated by its intrinsic advantages, geographic routing constitutes the focus of the current thesis.

A geographic routing is mainly distinguished by two components namely, the *location service* and the *forwarding strategy*. The location service is required to provide location information about nodes since in geographic routing; each node needs to know its own geographic location, the one of its direct neighbors and the location of the destination (commonly known as sink). The location can be generally obtained by GPS services or other localization techniques. As for the forwarding strategy, its aim is to advance data efficiently towards sinks. The most commonly used strategy in geographic routing literature protocols is greedy forwarding which makes routing decisions based on the distance between a candidate and the sink.

PROBLEM STATEMENT

Despite its substantial advantages, geographic routing can be strongly affected by two significant factors namely the mobility of nodes and the location accuracy. In one hand, mobility can affect geographic routing in two ways:

- Out-dated location information
- Fragile connectivity between neighbors

Strongly connected, these two mobility– induced issues can affect each phase of the geographic routing:

- *On localization service*: as mentioned earlier, data routing in geographic routing relies on the knowledge of the node's location, the locations of its neighbors and the location of the sink (s).
    - If sinks are mobile and move with unpredictable mobility, it becomes harder for sensor nodes to keep updated about their new locations.
    - If sensor nodes are mobile, it is difficult for mobile nodes to keep updated about the new locations of their neighbors in such dynamic networks especially with high mobility scenarios as nodes may move far from the previous stored positions, which lead to routing failures.

    Geographic routing should cope efficiently with the frequent change of nodes' positions, either those of their neighbors or the sink.

    Mobility of nodes affects also the location service in the sense where the location provider (either GPS or other technique) cannot localize a moving node with precision. A node in motion may fail to receive signals or location beacons from the location references. Hence, mobility can jeopardize the location service accuracy.
- *On the forwarding strategy*: routing decisions relying only on distance-based greedy forwarding in a mobile context is no longer sufficient, as a selected relay may be heading towards an opposite direction from the sink. Geographic routing should also consider mobility patterns of nodes when making routing decisions.

    Moreover, due to mobility of nodes, transmission links between neighbors are susceptible to break at any time. Even if a node identifies successfully its neighbors and chooses the right relay neighbor, if this relay node moves out of the transmission range of the sender before or during data transfer (it means the link breaks), the packet will be lost. Routing algorithms should consider link reliability when making routing decisions especially in the case of high mobility.

    Furthermore, mobility of nodes can cause intermittent connections, isolation of certain nodes, and even the occurrence of local maximum problem. Ignoring such situations leads to routing performance degradation.

On the other hand, geographic routing relies generally on exact positions of nodes. However, this assumption is unrealistic in real world deployment and location errors are inevitable even when using GPS. Mobility of nodes makes it even harder to get the exact location and may increase significantly the location errors of nodes. Neighbors declared closer, in reality may not be which leads to wrong forwarding and routing decisions.

Hence, the non consideration of mobility of nodes and their locations errors can lead to wrong routing decisions, which in turn, leads to routing performance degradation expressed by poor data delivery and increases in latency and energy consumption.

RESEARCH VACANCY AND CONTRIBUTIONS

Geographic routing research works in MWSNs can take two directions, one focusing on mobility management, either the mobility of sinks (mWSNs) or the mobility of sensors (MWSNs); and one focusing on the location management. The lack of studies dedicated specifically to those research works led us to investigate, in chapter 2, their effects on routing decisions and to review literature geographic routing protocols that consider mobility management and location error management. This review helped us to identify the main challenges of geographic routing and to uncover some research gaps that will be handled by the contributions of this thesis. Therefore, the objective of the present work is to design geographic routing algorithms, mobility friendly and resilient to localization errors while responding to network requirements and ensuring high performances.

The different contributions of this thesis are summarized as follows.

1- Reviewed geographic routings protocols for mWSNs mainly tackle the location service of the mobile sink; and how sensor nodes get the update of the sink's new location. However, mobile sink location discovery is not the only issue with sink mobility. Other issues related to mobility of sinks may affect positively or negatively the routing process such as the number of sinks, the presence/absence of the sink, the trajectory and speed of the sink.
    - ✓ In chapter 3, we propose a geographic routing that supports more characteristics related to sink mobility and copes with its side effects.

2- Most of geographic routing protocols for MWSNs consider GPS-enabled mobile nodes. Knowing that the network infrastructure setup with GPS is very expensive and energy draining, it would be better if new methodologies that provide cost effective and energy efficient location updates are explored further especially when dealing with random mobility patterns.
    - ✓ In chapter 4, we propose two GPS-free mobility prediction-based localization algorithms for mobile sensors with random mobility patterns.

3- As previously mentioned, location awareness is fundamental for geographic routing. Most of the geographic protocols proposed in the literature assume that nodes can get their positions either by using GPS or other localization technique without mentioning which method was really used in case of non-GPS provided location. This makes interested reader or industrial confused whether the whole solution can be deployable in real world scenarios. We believe that since the locations of nodes are necessary to make routing decisions, any geographic routing proposal should make clear which localization method was used to obtain nodal positions.
    - ✓ In chapter 5, part of our proposal, we execute in parallel and jointly a localization algorithm with the proposed geographic routing. Thus making the used location service known to the reader.

4- In geographic routing for MWSNs, neighborhood discovery is a paramount. Most of proposed geographic protocols adopt a proactive periodic beaconing process neglecting its influence on the routing performance. However, in dynamic and mobile scenarios, this strategy consumes unnecessarily node's energy since discovered neighbors will change over time and neighborhood table will be quickly outdated.
    - ✓ In chapter 5, and part of our proposal, we propose a reactive on-demand adaptive beaconing strategy where beaconing interval bounds are adapted to the mobility of nodes.

5- Earlier geographic routing schemes for MWSNs adopted blindly the greedy forwarding strategy that exploits the distance between nodes and sink. However, in mobile context, distance-only-based routing decisions are no longer sufficient.
    - ✓ In chapter 5, we propose a new relay selection strategy that considers nodal mobility patterns when making routing decisions and under realistic network models.

6- Most of geographic routing protocols make the assumptions that nodes are aware of their exact locations. This assumption is unrealistic in real world deployment as location errors are inevitable. Some works consider localization error in routing decisions but most of them were proposed for static networks, while those proposed for mobile networks dealt only with GPS-induced errors.
   - ✓ Knowing that mobile nodes change their locations frequently so their location errors also change over time, in chapter 5 and part of our proposal, we consider localization errors resulted from GPS-free mobility-prediction-based localization method in routing decisions and relay node selection.

7- Local maximum/dead end problem is one of the main concerns of geographic routing. Many proposed protocols tried to resolve this issue when it occurs by finding an alternative path and bypassing it using planarization or other similar strategies.
   - ✓ In chapter 5, part of our proposal, and without the need for planarization, we take advantage of nodes' mobility to anticipate and reduce the occurrence of local maximum by considering nodes -which would be normally ignored in standard greedy forwarding- as valid candidates if they have the potential to make advance towards the sink.

8- Besides proposed protocols for VANETs, most of geographic protocols for MWSNs consider mobile nodes with a large pause time, which makes a mobile node, converge into a static node during this time, whilst the challenge for geographic routing in such dynamic networks comes from the lack of link reliability induced by high mobility especially during data transfer when nodes are continuously moving.
   - ✓ In chapter 5, we propose a geographic routing scheme that can be well applied in case of continuously moving nodes where we consider the link reliability in routing decisions.

9- Mobility of nodes can cause intermittent connections in the network. Ignoring these potential disconnections may lead to performance degradation of the routing.
   - ✓ Our proposed geographic routing, detailed in chapter 5, can be well applied in intermittently connected networks.

THESIS OUTLINE

This thesis comprises five chapters and, following the introduction, it is organized as follows:

Chapter 1 comprises an overview and generalities about mobile wireless sensor networks, their characteristics are also exposed, their advantages over static networks and then we classified them according to their mobilizer entity. Their different applications and the potential applications related to this thesis are then presented. MWSNs have also many challenges. We outlined in this chapter mainly the challenges addressed in this thesis.

Chapter 2 addresses the problem of routing in WSNs and its requirements before focusing the study on geographic routing and its challenges. A review of geographic routing for MWSNs is then investigated where a number of routing protocols especially designed for MWSNs are presented following a new taxonomy based on the management of mobility and location errors. An analysis and discussion about the challenges of such routing strategies are discussed at the end of this chapter. By understanding the network challenges and the solutions provided by previous proposed algorithms, the unsolved issues can be identified and addressed accordingly.

Chapter 3 highlights in depth more characteristics of sink mobility such as the number of sinks, their mobility nature, and their potential absence/disconnection from the network and their trajectories. We then propose a geographic routing for networks with mobile sinks that supports these additional patterns of mobile sinks and that can cope with their side effects if any. This chapter corresponds with *contribution 1*.

Chapter 4 tackles the challenge of getting continuously the location information of mobile nodes when those nodes move with unpredictable mobility patterns and comes up with propositions of two localization algorithms that benefit from the presence of mobile anchors/sinks to predict the mobility of nodes. The prediction allows nodes to be aware of their mobility patterns even without using GPS and to reduce their localization errors. The chapter presents *contribution 2 and 3*.

Chapter 5 represents the main contributions of this thesis where an intertwined localization and routing scheme is proposed called INTEGER. This new approach is in response to the problem of routing in mobile networks under more realistic assumptions, particularly in the presence of location errors and with unpredictable mobility of nodes. INTEGER combines mobility-prediction based localization, a mobility adaptive on-demand neighborhood discovery, relay weighted selection and delay-tolerant geographic routing. This chapter includes the rest of the contributions listed in the previous section.

We conclude this thesis by summarizing the key results and highlighting the possible future research directions for the problems and solutions presented in the thesis.

Background
And
Literature Review

Chapter 1: Mobile Wireless Sensor Networks
Chapter 2: Geographic Routing in Mobile Wireless Sensor Networks

CHAPTER 1

Mobile Wireless Sensor Networks

INTRODUCTION

The era of the 21st century belongs to the wireless world. The rapid growth of cellphones, wireless LANs and wireless internet is driving the whole world towards integrity with wireless communication. The improved availability of sensor nodes has caused an increase in the number of researchers studying wireless sensor networks. More recently, the advances in mobile robotics allow us nowadays to include the mobility perception into various and different classes of Wireless Sensor Networks (WSNs). Indeed, the use of mobile sensors is possible and useful in many application scenarios, ranging from environmental monitoring and public safety applications, to the industry, healthcare and military applications. In this chapter, we present general concepts of Mobile Wireless Sensors Networks (from here and forth we refer to them by MWSNs), their advantages over static WSNs, their mobility classes, their applications and challenges. We then outline the challenges addressed in this thesis.

1. GENERALITIES AND CHARACTERISTICS OF MWSNS

A mobile wireless sensor network (MWSN) consists of a set of sensor nodes that have the ability to move within the network. In fact, mobility can be achieved by equipping the sensor nodes with mobilizers to move (as shown in figure 1) or the sensors can be made to self-propel via springs [1] or wheels [2] or they can be attached to transporters like vehicles, humans, animals, robots [10] , etc. Figure 2 shows an example where wheels are attached to the sensor.

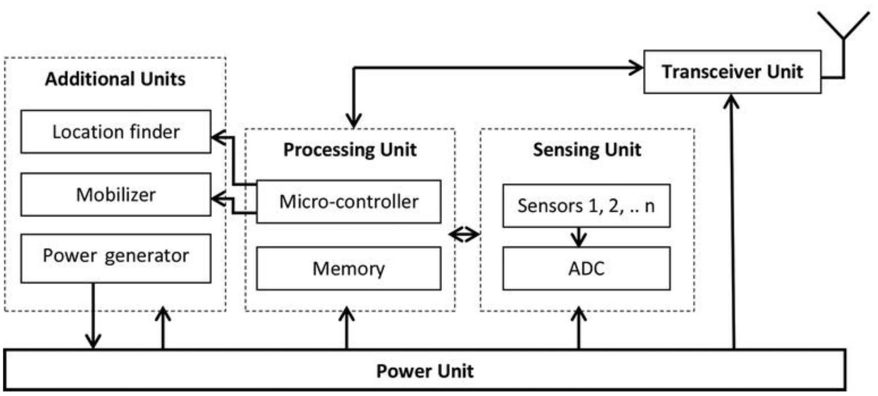


Figure 1: Architecture of mobile sensor node with additional units for mobility and localization.

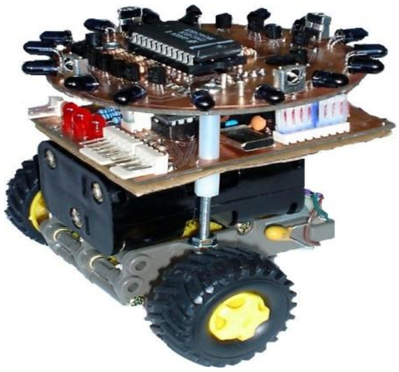


Figure 2: A sensor with wheels.

Sometimes the sensor nodes may move due to the environment (ocean or air) in which they are placed [3]. Based on communication type, two kinds of mobile wireless sensor network exist at present. One is known as the infrastructure network, in which the mobile unit is connected with the nearest base station that is within its communication radius [4]; as in the current mobile telephone system. The other one is called infrastructure-less mobile network [5], also known as ad hoc network. No fixed routers are needed and mobile units are capable of movement and still being able to self-organize and establish communication in an arbitrary manner. Figure 3 shows the two types of networks. In this thesis, we are interested in the latter type of network.

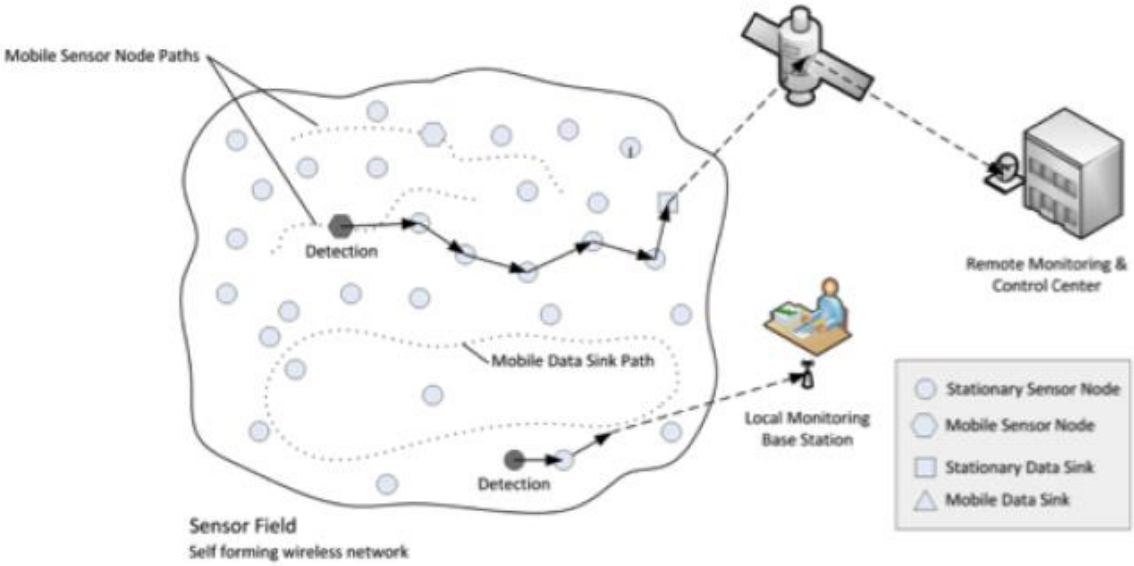


Figure 3: types of sensor nodes and networks.

2. ADVANTAGES OF MOBILE WIRELESS SENSOR NETWORKS

The recent researches prove that mobile wireless sensor networks outperform the static wireless sensor networks [6, 7, 8]. Main advantageous over static networks are [5-9] :

Long network lifetime: The lifetime of a sensor network can be increased using mobile sensor nodes. For example, in static networks, nodes that are closer to the sinks "die" soon from energy depletion causing a disconnection of the sinks from the rest of the network. We term the problem of energy drainage at the sink's neighbors the "sink's hotspot". In contrast, if the sink is mobile or the nodes are mobile, the neighborhood would change, hence the energy can be automatically balanced between nodes.

More channel capacity: Mobile wireless sensor networks are believed to have more channel capacity compared to static WSN. For example, the capacity gain has been calculated in case of mobile sink within WSN and has come out to be 3-5 times more than static WSN, provided the number of mobile sinks increases linearly with the number of sensor nodes.

Better targeting: Because sensors are mostly deployed randomly instead of precisely, they are generally required to move for better sight or for close proximity, which is favorable for targeting.

Cost Reduced. Moving to a less dense mobile WSN means fewer nodes are deployed, subsequently reducing the network cost. Although adding mobility features to the sensors might be expensive, in many cases it is possible to exploit mobile elements already present in the sensing area (e.g., vehicles, moving equipment, mobile personnel [11]) and attach sensors or sinks to these elements.

Improved connectivity: unlike in static WSNs where an initially-connected network can turn into a set of disconnected sub-networks due to hardware failure or energy depletion, mobility can help in a better quality of communication between sensor nodes. In addition, in a sparse or disconnected network, this property is especially helpful to maintain efficient network connectivity and to auto-reorganize the network.

Data fidelity: It is well known that the probability of error increases with the increase of the number of hops that a data packet has to travel through. But in MWSNs, the reduced number of hops due to mobility will increase the probability of successful transmissions. This not only increases the quality of data received but also, it further reduces the energy spent by reducing the retransmissions required due to errors.

Dynamic Nature: Due to the mobility, MWSN has a much more dynamic topology compared to the static WSN. It is often assumed that sinks or even sensor nodes move continuously in a random fashion, thus making the whole network under a very dynamic topology.

Flexibility: Mobile sensors can relocate themselves after initial deployment to achieve the desired density requirement and reduce the energy holes in the network.

Energy Efficiency: Mobility can reduce energy consumption during communication [5]. For example, exploiting the mobility of data sinks has been widely accepted as an efficient way to alleviate the hotspot issue in WSNs and further prolong the network lifetime. The hotspot issue commonly refers to the sensor nodes near static sinks consuming energy much faster than sensor nodes in other regions of the network. The hotspot issue is caused by the converging nature of traffic in WSNs with static sinks. However, in a WSN with mobile sinks, the high data rate near sink(s) can be distributed to a greater number of sensor nodes as the sink(s) move and change their neighborhood so that the energy consumption is more evenly distributed, which leads to much longer network lifetime.

3. CLASSIFICATION AND APPLICATIONS OF MOBILE SENSOR NETWORKS

To better understand the different applications of MWSNs, we propose to following classification. This classification is based on three main axes. According to the mobilizers of nodes, the mobility patterns of nodes and which nodes are mobile.

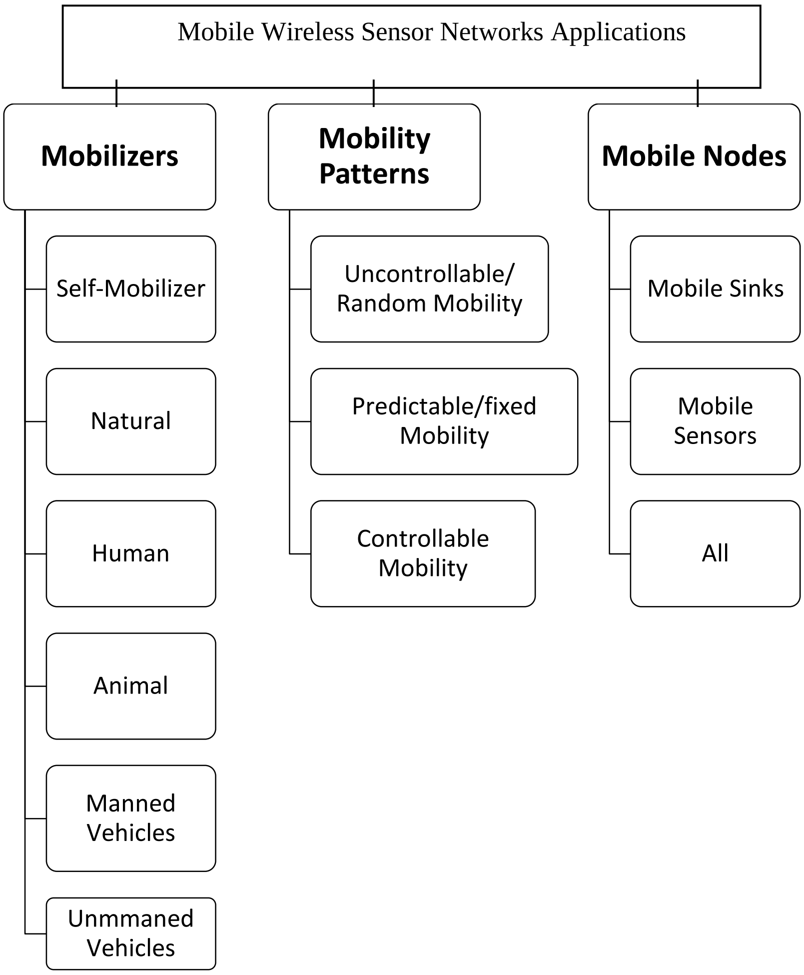


Figure 4: Classifications of MWSNs.

3.1 CLASSIFICATION BASED ON MOBILITY OF NODES

There are three main ways to introduce mobility in a MWSN. The simpler one is to have static sensor nodes while the sink nodes are the ones moving. The second approach is to maintain static sinks while sensor nodes are mobile. Finally, both approaches can be combined, letting all nodes in the WSN be mobile.

Networks where only sinks can be mobile

Wireless sensor networks with mobile sinks (mWSNs) have attracted much attention in recent years. Such networks typically consist of many static sensor nodes for sensing and one or multiple mobile sinks (MSs) for data collection [12]. These mobile sink nodes roam over the sensing field and collect sensed data from sensor nodes. Mobile sinks can be mounted on various moving objects: vehicles, robots, people, and so on, making mWSNs suitable for a wide range of applications. For example, in environment monitoring applications, forest rangers can carry wireless communication devices to collect data from sensor nodes deployed in a mountain area [13]. Another example, crops on a farm may have sensors which take measurements about the humidity or temperature of the soil and the atmosphere; the smartphone of the farmer can act as a sink node, so whenever a farmer walks by the farm, the sink collects the measured data. In military surveillance applications, moving soldiers can collect information about hostile objects from the sensor nodes pre-deployed in the battlefield. In building safety applications, moving buses equipped with wireless communication devices can collect information about structural status of the nearby buildings.

Networks where only sensors can be mobile

In such networks, the sink is static commonly known as base station while sensors may be attached to or carried by mobile entities, or they may possess automotive capabilities [13]. Some scenarios with mobile sensors include: sensors connected to vehicles in big cities to study traffic conditions and routing planning [15]; sensors floating on rivers [10]; NASA's project on exploration of Mars, with sensors driven by winds [16]; sensors in mobile cellular networks where road traffic information and weather conditions can be extracted from smart phones [4].

Networks where all nodes can be mobile

In these networks, all nodes can move at any time. An application such monitoring animals can be a good example of such networks where sensors are attached to animals in the wild and each animal moves with its own speed and takes its own direction. The mobile sink can be a drone sent to collect data from sensors attached to animals to not disturb them with any human presence and to avoid risky situations with wild animals. A healthcare application where monitoring patients is also a showcase where all nodes can be mobile. In such application, wearable sensors on patients send medical data related to patient' health to mobile devices carried by doctors or assistant personnel [17]. Tracking soldiers in battlefields and tracking emergency responders in disaster areas are also applications where mobile sensors are in the heart of the system [18,19].

3.2 CLASSIFICATION BASED ON MOBILITY PATTERNS OF SENSOR / SINK

There are three main mobility patterns in a MWSNs' applications:

Uncontrollable Mobility: which means a node moves in a random fashion [14]. The mobility of a node can be considered as uncontrollable (or random) if the motion characteristics (i.e. direction, speed, and trajectory) of the node is not related to or determined by the data routing requirements [22]. It is regulated according to the primary purpose of the user (i.e. people, vehicle) carrying the node in the sensor field. For instance, the purpose of a fireman carrying a sensor and/or sink node is eliminating fire in the fire field while getting information about the situation from the sensor network deployed in the field, thus his movement is designated by his primary task. Therefore, the sensor/sink mobility is considered as uncontrollable in such a scenario. The main challenge in this kind of scenarios is how to deliver data from a source node to sinks when the intermediary sensor nodes and/or sinks are randomly moving in the network.

Predictable/Fixed Mobility: Predictable mobility refers to the case when the motion is known but cannot be changed [20]. Fortunately, this knowledge can be exploited to route data. Predictable sink/sensor mobility can improve energy efficiency of data transmission [23] by combining data relaying with predictable mobility. Sensors can predict the time of data transfer knowing the trajectory of the mobile node [21]. That way, sensors go into a sleep state to save their energy and become active again just during the time of data transfer. A representative example of predictable mobility is the vehicular mobility such as in public transportation (i.e. train, bus). Such vehicles can act as mobile sinks in wide areas for applications such as pollution monitoring [24].

Controllable Mobility: The mobility of a node can be controlled by the user. Controllable mobility, such when sensors mounted on a robot or UAV [25], can be used as means for improving network connectivity and data dissemination tasks [26]. The controlled mobility of sensor nodes is generally used to achieve optimal deployment or to cover holes to improve the connectivity or the sensing coverage [28]. Sink mobility is controlled usually for the purposes of avoiding hot spots around the sink and distributing energy consumption throughout the network evenly or enabling single-hop communication between the sink and the source nodes to avoid long-range communication. In these approaches of exploiting controlled mobility of sink, the problem is mostly about finding the optimal motion of the mobile sink to balance the energy consumption in the network or scheduling the mobile sink in real time to visit source nodes such that to avoid loss of packets or overflow of the sensors' buffers [27].

3.3 CLASSIFICATION BASED ON MOBILE PLATFORMS

One of the main motivations behind the study of MWSNs is its large number of emerging applications especially in the era of Internet of Things (IoT). The fact that nodes may be allowed to move freely, means they can be attached to a variety of mobile platforms without compromising performance.

There are four main categories of platforms that can enable the mobility of sensors, namely people, animals, manned vehicles and unmanned vehicles. Add to that the case where sensors are designed with self-mobilizers or they move influenced by some natural parameters like wind or rivers. The different platforms are described below along with example applications:

Self-mobilizers

The design of mobile sensors includes an additional unit for the mobility where a micro-dynamo is added to self-propel the sensor making the sensor as a small robot [29].

Natural parameters

Sometimes sensor nodes move from one place to another due to natural factors such as an unintentional displacement by an animal or environmental parameters such as wind or river flows or oceans to measure direction and speed of ocean currents [30].

People

People are a primary source of mobility for both wearable sensors and sensors in objects. For example, in a smart home application, items such as smart phones and tablets can act as mobile sinks, carried out by people. They could gather data from devices such as a refrigerator, oven, thermostat, security cameras or television. A smart hospital could also monitor health and fitness data from a user wearing body sensors [31]. Since the mobile devices are considered to be battery powered, energy consumption will need to be kept low. Additionally, as people carry them, the lifetime of the devices should also account for the time between available places to recharge their batteries.

Animals

Sensors attached to animals may be used to gather information such as location, body temperature, ambient temperature, food nature. This information can be then reported back to the sink for analysis by researchers to determine migration and feeding habits, as well as the health of the animals. Similarly to devices carried by people, there nodes will be battery powered, however they may be expected to last for months or years. As such, applications using this platform are the most power restrictive; so devices and protocols used will need to be very energy efficient. Additionally, these applications will need large amounts of memory, but the delay requirements are relaxed and they can be even delay-tolerant [32]. This is because animals move freely and nodes may be disconnected temporarily from other nodes since the network area will be much large.

Manned Vehicles

Sensors may also be attached to vehicles such as cars, trains, busses, bicycles or motorbikes [33]. In the case of road vehicles, the sensors could be tracked by a central authority, to determine traffic patterns and areas of congestion [34]. This information can be used to route users around areas with potentially long delay and alleviated congestion. In the same way, the data can also aid the emergency services in responding faster to call outs. Generally, vehicles have a large on-board power supply, which gives the node more freedom in terms of power consumption. However, the high speeds of vehicles may cause a frequent change of topology, which may create difficulties to routing protocols.

Unmmaned Vehicles

The use of unmanned vehicles is nowadays very affordable and drones can be integrated in a vast array of applications. One example is aerial surveillance in hostile environments or search and rescue applications [25], whereby some unmanned vehicles are equipped with sensors to locate soldiers, emergency responders or disaster victims, take photos and videos to construct area maps. Figure 5 shows an example of UAV usage. An on-board power supply is usually available and the use of solar power is also practical.

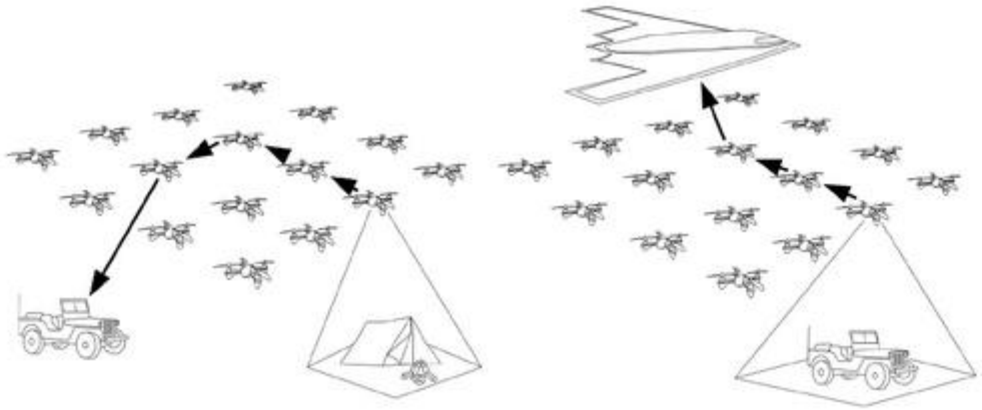


Figure 5: MWSNs'Applications using UAVs.

UAVs as mobile sinks

The recent advances in technology of unmanned aerial vehicles (UAVs) allow their usage as a part of the WSNs. UAVs provide an extremely flexible platform for WSNs applications by playing different roles in WSNs such as actuators, sensors, and mobile sinks [35]. In some monitoring scenarios such as animal monitoring, the sensed information is time-tolerant since collected data are generally to be studied and analyzed afterward [36], even though a reduced delay would be preferable. Energy-efficient solutions are paramount for sensor nodes since catching wild animals in the purpose of recharging their sensor batteries is not an easy task and not practical. Also, sending people to gather data from wild field animals is very risky and can disturb the animal's behavior. Meanwhile, the arise of UAVs provides cost-effective and appealing solutions for tracking applications and the

UAV can be sent to accomplish missions of collecting data from hostile areas and dangerous zones [25]. Figure 6 shows an example of a deployed UAV as a mobile sink to collect data from ground sensors.

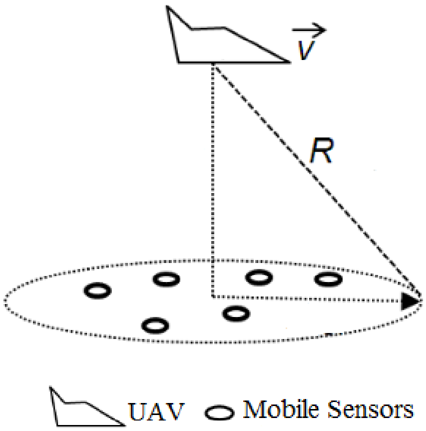


Figure 6: A drone monitoring mobile sensors.

4. APPLICATIONS RELEVANT TO THE THESIS

Animal Monitoring using Mobile Sensor Networks

Wildlife monitoring is an important example that has involved intensive research activity in the past few years [36]. In particular, biologists have long recognized the need for insight into animal habitat, the need for monitoring endangered species, and the need for studying animals' behaviors and movements. These studies are necessary to understand the physiology, behavior, and the ecology system of the animals [36-37]. However, many wild species are, by nature, free-roaming and wide-ranging which makes it too difficult to track and monitor their behavior through human intervention, thus calling for automated monitoring systems which demand less human presence in the field is much practical [39]. In addition, human presence may disrupt animals' normal activities.

Many animal tracking technologies have been proposed and implemented by engineers and wildlife researchers [36-41]. One main technology is the wearable GPS-based animal tracking devices. Juang et al. [42] present their ZebraNet project in which a low-power wireless system is built for position tracking of zebras. Tracking nodes are installed on zebras and record GPS positions of zebras periodically. In their research, they investigate system design ideas, communication protocols between tracking nodes, and how sensor specifications such as battery lifetime and weight may limit the system performance [43]. Other recent researches [44]– [45] on animal behavior gather animal movement data by installing wearable GPS devices called Collars. Hence, sensor networks seem to be a more feasible and reliable choice for animal monitoring. Figure 7 shows an example of sensor devices attached to lionesses.

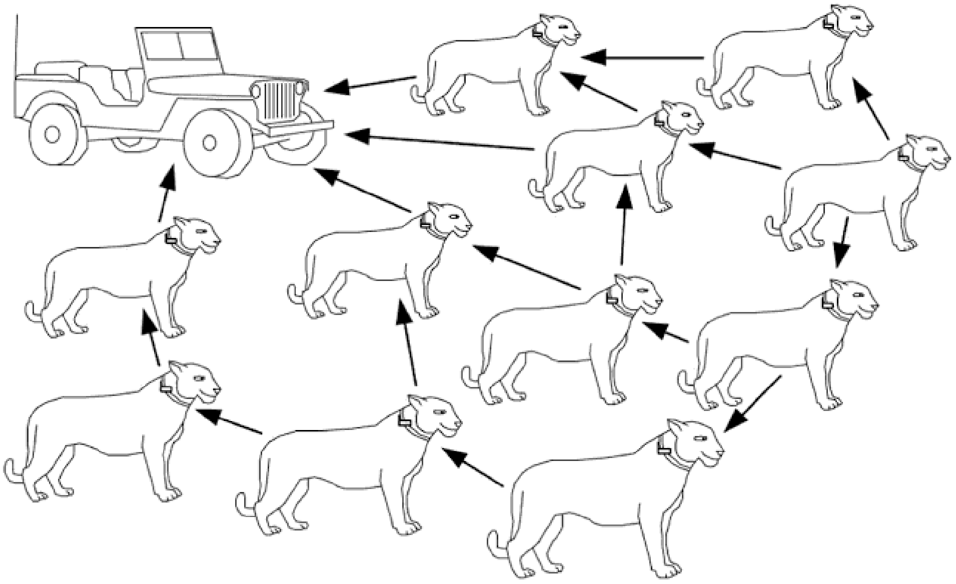


Figure 7: Animals equipped with sensors that transmit data to a mobile sink.

However, when considering a large scale monitoring, attaching a GPS-device on each animal can be very costly. In addition, it could be bulky and disturbing for the animal. Also, monitoring animals in wild field does not necessitate high location precisions and estimations can be often sufficient. UAVs can be sent as data collectors and can play the role of mobile anchor that helps sensor nodes to localize themselves. The challenge here is to ensure having continuously the animals' locations and routing sensed data with nodes having uncontrollable movements, which is the scope of this thesis.

Environmental parameters Surveillance: sensors that measure environmental measurements such as temperature, humidity, air pollution, etc can be placed in strategic places [42]. Manned vehicles (bikes, cars, trains, etc) passing by the sensed fields or unmanned vehicles (UAV, UUV) sent on purpose to the sensor area can play the role of mobile relay nodes or mobile data sinks respectively [35].

Underwater monitoring: that is submerging a network of sensors in an ocean bed to detect debris from plane crashes for recovery and identification purposes. In this case, beyond (partially) mobile sensors, the network comprises unmanned or autonomous underwater vehicles (AUV) that are sent roaming through the network [43] for data collection.

Emergency Response: Emergency Response and Disaster Management Systems that use WSNs have received much attention by researchers in the last five years [19]. This interest comes from the increasing number of disasters all around the world, causing the loss of a huge number of lives and properties. In Algeria, authors of [18] proposed a solution to locate and monitor the first responders in a rescue mission using wearable sensors. The Algerian project in which we are members described in [144] also proposed a whole scheme where a combination of different technologies was used including WSNs to monitor the disaster area and mobile sinks mounted on UAVs to automatically gather data.

5. CHALLENGES OF MWSNS

Independently from how mobility is achieved, it introduces a number of important issues that impact the performance of the network, factors which do not arise in static WSNs, we outline mainly those who are in direct relation with our thesis namely:

Mobility of Sink. In centralized WSN applications, sensor data are forwarded to a base station, where they can be processed using resource-intensive methods. Data routing and aggregation can incur significant overhead. Some MWSNs use mobile base stations, which pass across the sensing region to collect data, or to position themselves so that the number of transmission hops is minimized for the sensor nodes.

Continuous Localization. In statically deployed networks, node position can be determined during initialization. However, mobile nodes must continuously obtain their positions [46]. This requires additional time and energy, as well as the availability of a rapid localization service.

Routing in Dynamic Network Topology. Since there is no fixed topology in these networks, one of the greatest challenges is routing data from their source to the destination. Traditional WSN routing protocols typically rely on routing tables or recent route histories. In dynamic topologies, routing tables become quickly outdated, and route discovery must repeatedly be performed at a substantial cost in terms of power, time, and bandwidth. Currently there is still no standard for MWSNs, so often protocols from mobile ad hoc networks (MANETs) are borrowed. Unfortunately, although there is an active area of research dedicated to routing in MANETs, but MWSNs cannot rely on these works as MWSNs have their own characteristics, which are different from MANETs.

Power Consumption. Power consumption models differ greatly between WSNs and MWSNs. For both types of networks, wireless communication incurs a significant energy cost and must be used efficiently. However, mobile entities require additional power for mobility; an efficient energy management is required in this kind of networks.

Intermittent Connected Network. Dynamic topology, transmission failures, battery depletions can result in unreliable communication links, especially in hostile and remote areas leading to intermittent connectivity in the network. Hence routing protocols must be adaptive to this intermittence nature.

CONCLUSION

In this chapter, we presented mobile wireless sensor networks, their characteristics and advantages, their potential in modern applications and their challenges. This chapter is considered as the base stone to understand the scope of this thesis and the motivations and challenges that we aim to resolve by the different contributions of this thesis. In the next chapter, a detailed survey on geographic routing for MWSNs is presented where protocols are classified according to a specific taxonomy. Challenges related to geographic routing are also addressed.

CHAPTER 2

Geographic Routing in Mobile Wireless Sensor Networks: Review and Taxonomy

INTRODUCTION

Introducing mobility to the nodes can cause frequent changes in topology. This dynamic topology in mobile wireless sensor networks (MWSNs) causes problems for routing protocols, since there is no fixed path from source to sink. Mobile ad-hoc networks (MANETs) also share this problem; however, their requirements differ from those of a MWSN. As such, the problem of routing in a MWSN necessitates alternative solutions to those protocols designed for static WSNs or MANETs.

In his chapter, we address the problem of routing in WSNs before focusing our study on geographic routing and its challenges. A state of the art of geographic routing in MWSNs and a number of routing protocols especially designed for MWSNs are presented following a new taxonomy. An analysis and discussion about the challenges of such routing strategies are discussed at the end of this chapter.

1. REQUIREMENTS OF ROUTING IN WSNS

To design a routing protocol, some constraints related to wireless sensor networks' nature and their applications should be considered such as the reduced computing, radio and battery resources of a sensor. In the following paragraph, we will describe briefly some of the most important requirements that a routing protocol should fulfill [47-49]:

- **Autonomy:** a centralized entity that controls radio and resources could be an easy point of attack, thus, network nodes should make routing decisions by themselves.
- **Energy Efficiency:** in a WSN, most of the time, the battery replacement is not feasible and under some circumstances, the sensors are not even reachable. Thus, routing protocols should prolong the network life time while maintaining a good grade of connectivity to allow cooperation between nodes.
- **Scalability:** in some applications, a thousand of nodes are deployed, so routing protocols should work with such a large amount of nodes.
- **Resilience:** a routing protocol may consider cooperation between nodes to build a route. In case where some nodes stop operating, protocols should cope with this eventuality and an alternative route should be discovered.
- **Device heterogeneity:** in some applications, the introduction of different kind of sensors (acoustic, video, PDA, laptop, etc.) could report significant benefits. Routing protocols should deal with different processors, transceivers, power units or sensing components.
- **Memory and computational power:** memory and computational power limitations mean a routing protocol should be kept as simple as possible.

- **End-to-End Delay**: is defined as the time elapsed between the packet generation from the source until its reception by the sink. Many applications like emergency and health oriented networks rely on timely delivery of data so that it can be acted upon quickly. Other networks may accept large amounts of latency between gathering the data and its reception by the sink. These kinds of networks are referred to as Delay-Tolerant Networks (DTNs). Often these networks will be particularly sparse, with nodes being spread over large distances.
- **Mobility Adaptability:** In a mobile network scenario, an efficient routing protocol should support the mobility of nodes (sinks, events, etc.).

2. CLASSIFICATION OF ROUTING PROTOCOLS IN WSNS

Several routing protocols were proposed by many researchers, based on various criteria and design issues. No routing protocol can be termed as perfect, as each routing protocol may be suitable for some application but may have loopholes when judged in some other perspectives.

2.1 CLASSIFICATIONS

In the basic classification [51], routing protocols can be gathered into three categories, namely, **proactive**, **reactive**, and **hybrid** protocols depending on how the source finds a route to the destination. In proactive protocols, all routes are computed before they are really needed. This cannot be suitable for mobile scenarios where topology changes frequently. In reactive protocols, routes are computed on demand which make them better for mobile networks. Hybrid protocols use a combination of these two ideas.

According to [48][49], a routing protocol can be classified according to: a) the network structure and b) the protocol operation.

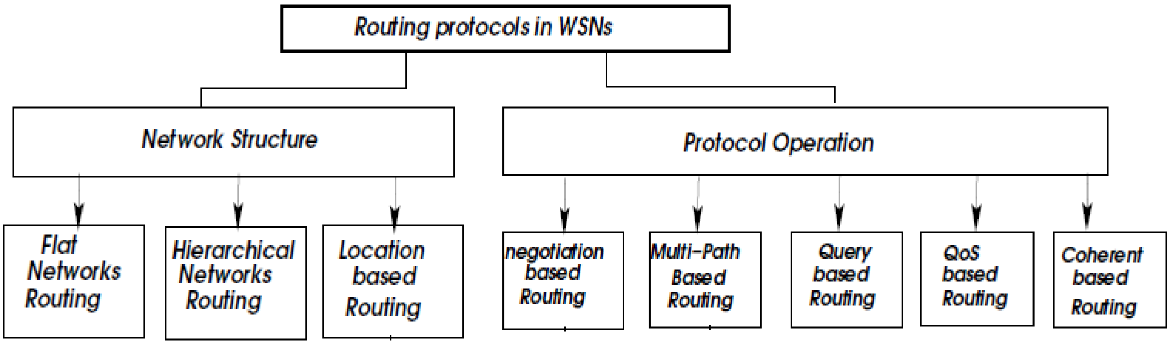


Figure 1: Classification of Routing Protocols according to [48][49].

In the first class, we distinguish three types of protocols:

1- **Flat schemes:** all the sensors participate with the same role in the routing procedure.
2- **Hierarchical architecture:** the network is divided into clusters or groups. A leader or a cluster head is selected in the group to coordinate the activities within the cluster and to communicate with nodes outside the own cluster. The differentiation of nodes can be static or dynamic.
3- **Geographic protocols:** also called position-based or location-based protocols. These protocols take advantage of the location information to make routing techniques more efficient. Specifically, neighbors

exchange information about their location so when a node needs to forward a packet, it sends it to the neighbor which is assumed to be closest to the final destination. The location information used in geographical algorithms can be derived from specific devices such as GPS or other localization technique.

In the second class, the routing protocols are classified according to the operation technique of the protocol. We differentiate the following categories:

1- **Negotiation**-based**:** These protocols use high level data descriptors in order to eliminate redundant data transmissions through negotiation. The main idea of negotiation-based routing in WSNs is to suppress duplicate information and to prevent redundant data from being sent to the next sensor or to the base station by conducting a series of negotiation messages before the real data transmission begins.
2- **Query**-based: in this kind of routing, the destination nodes propagate a query for data (sensing task) through the network. The node having this data sends back the data that match the query to the destination node that initiates the query.
3- **QoS**-based: in QoS-based routing protocols, the network has to balance between energy consumption and data quality. In particular, the network has to satisfy certain QoS metrics when delivering data to the Base Station, e.g., delay, energy, bandwidth, etc.
4- **Multipath**-based: to increase reliability and the performance of the network, paths should not share any links.
5- **Coherence**-based: in coherent routing, the data is forwarded to aggregators after including tasks such as time stamping. To perform energy-efficient routing, coherent processing is normally selected.

2.2 SCOPE OF THE THESIS

According to literature [47-56], we observe that previous geographic routing protocols were proposed mainly for stationary WSNs or for MANETs and recently a number of geographic routing algorithms were proposed for Vehicular Ah Hoc Networks (VANETs). In contrast, the focus of this chapter is to highlight the research vision and potential for applying geographic routing in MWSNs, which is not yet well investigated especially when all sensor nodes are mobile and with uncontrollable mobility. In fact, under the mobile scenario, the variation of network topology arising from nodal mobility is mainly the challenge for routing in MWSNs. However, it is difficult to obtain the most recent network topological information given such condition. Proposed routing protocols generally draw inspiration from the two fields; WSNs and MANETs. However, stationary WSN routing protocols provide the required functionality but cannot handle the high frequency of topology changes. Whereas, MANET routing protocols can deal with mobility in the network but they are designed for two-way communication, which in sensor networks is often not required [57]. As for VANETs protocols, they do not cover all mobility scenarios as vehicles generally have predictable mobility following map/road-based mobility.

In terms of research vacancy, based on our observation deduced from our review to surveys in [47-63], in figure 2, we show the number of proposed geographic routing in the literature for each sub-class of WSNs. For example, in [60] which represents the most recent survey on routing for MWSNs, there have been only 6 geographic routing protocols reviewed compared to other numerous non geographic and only 2 consider the total mobility of nodes. This lack of attention is because MWSNs are still an emerging branch of networks and handling all their challenges was not possible with previous technologies.

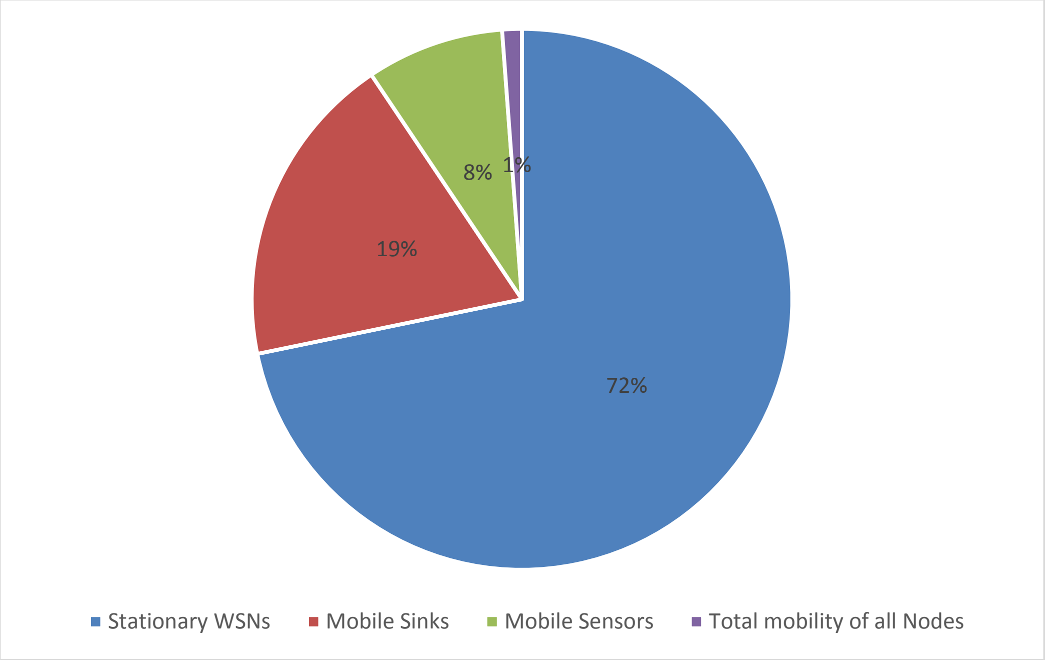


Figure 2: Geographic Routing Protocols for WSNs in the literature.

In terms of research feasibility, geographic routing inherently is without the requirement of contemporaneous end-to-end connectivity which makes it a very suitable choice for MWSNs where topology changes frequently but with the additional challenge of having continuously the location of mobile nodes.

In this chapter, we first, present the basic concepts of geographic routing and its techniques. We then focus the study on specific classes. For each sub-class, we present some motivations of use and state of the art of recent protocols. Hence, the major contributions of this chapter are as follows:

(i) Identify the research motivation and challenges for bringing geographic routing protocols in MWSNs.
(ii) Provide an up-to-date review on recent geographic routing protocols in MWSNs, following our original taxonomy.
(iii) Highlight potential directions leading the ongoing research in this explicit branch.

3. GEOGRAPHIC ROUTING IN WSNS

Often, WSN protocols are adapted for MWSNs by adding functionality to allow them to cope with the mobility of nodes. However, the hierarchical protocols have an inherent delay in setting up clusters and they also need data aggregation to combine multiple packets of similar data into one message. In addition, high mobility can cause nodes to switch clusters regularly, which consumes a lot of delay for a node to join a new cluster. Flat routing is preferred in mobile networks due to their ability to cope with frequent topology changes. Since all nodes are equal, algorithmic complexity is reduced. However, they are generally not scalable [47]. Geographic protocols are currently being thoroughly studied due to their application potential in networks with high demanding requirements. Their main characteristic is that they make use of location information for routing decisions since sensor nodes are addressed only by means of their locations [56]. Geographic routing seems to be the most adequate for MWSNs since forwarding decisions are made only among neighbors.

3.1 MOTIVATION OF USING GEOGRAPHIC ROUTING PROTOCOLS IN WSNS

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 [56]. Geographic routing protocols require only location information which is needed, in most cases, to calculate the distance between two nodes. Thus, they are very efficient in wireless networks for several reasons. First, nodes need to know only the location information of their direct neighbors in order to forward packets and hence the state stored is minimal. Second, such protocols conserve energy and bandwidth since discovery floods and state propagation are not required beyond a single hop. Third, in mobile networks with frequent topology changes, geographic routing has fast response and can find new routes quickly by using only local topology information [60]. Thus, there is no establishment and maintenance of routes as happens in topology-based routing algorithms. This property is important given the overhead required for maintaining the routing tables updated in highly mobile scenarios. Therefore, it is generally considered as an attractive routing method for both mobile wireless ad-hoc and sensor networks. Other criteria that make geographic routing very suitable for many applications are listed below [47, 54, 56]:

- **Simplicity:** geographic routing protocols are based on simple calculations since nodes need only geographic information to route packets such as node’s coordinates and distances between nodes.

- **Stateless architecture:** in non geographic routing, nodes containing information referring to the cost of the links to certain neighbors, the range of some nodes, node status, energy level, velocity, activity, cryptographic keys and destination nodes, are considered as state-full nodes since they need memory to store this information. Otherwise, in geographic routing, the nodes are considered to be without memory requirement (stateless algorithms) since they do not need a routing table especially for MWSNs where the topology changes frequently. All what they need is to maintain knowledge about their direct neighbors.

- **Autonomy**: in geographic routing, nodes make routing decisions by themselves according to neighborhood location knowledge. There is no need to a centralized unit to control and assist the routing procedure.

- **Energy Efficiency:** One big advantage of geographic routing schemes is the fact that there is no need to send out route requests or periodic connectivity updates. This can save a lot of routing overhead and consequently, energy of nodes. This is an important consideration for sensor networks where the network size could be on the order of thousands of nodes, and each node has extremely limited memory capacity to store routing tables.

- **Scalability:** wireless sensor networks have variable 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 can be valid for geographic routing since a newly joined node has only to execute a simple exploration of its neighborhood.

3.2 COMPONENTS OF GEOGRAPHIC ROUTING

A geographic routing protocol is mainly distinguished by two components namely: the *location service* and the *forwarding strategy*.

3.2.1 Location Service

Geographic routing requires three necessary conditions that need a suitable location service, First, each node must know its own location information, GPS or other location method can provide the location of the node ; Second, each node must know the location of its one-hop neighbor nodes. This requirement can be fulfilled via beacon messages that contain location of neighbors and other information specific to each routing scheme; third, the source node must know the location of the sink (s), in order to encapsulate this location in each packet so that relay nodes can calculate the distances between candidate nodes and sinks. In case of mobile sink, sensor nodes should get the new sink location after displacement.

a) Self-Location Awareness

Most of geographic protocols suppose that nodes use the Global Positioning System (GPS) to be aware of their locations. The advantages of GPS range from its planetary coverage, availability in modern devices, and relative accuracy in ideal conditions. However, GPS may fail to give accurate positions under some circumstances such the NLoS-Non Line of Sight (for instance, under a tunnel) and obstacles (for instance, inside buildings). In addition, GPS is cost effective especially if an application needs hundreds or thousands of sensors (for instance, Agriculture application). Moreover, the frequent GPS location check is energy draining which makes it not practical. Some other localization techniques can be found in [64] that can be used to overcome the problems of GPS and to reduce the cost and energy of sensors. Some of them are anchor-assisted as in cellular networks [65] where some estimation techniques can be used such as triangulation, angulations, the signal strength, etc. For example, the Received Signal Strength Indicator (RSSI), where the strength of the signal is analyzed to determine the distance between the mobile node and the base station. Besides the RSSI, techniques like the Time of Arrival (ToA) [67] can be also used, which is based on the amount of time that the signal of a device takes to reach the anchor, and the Time Difference of Arrival (TDoA) [67], which is based on the difference of time that the signal takes to reach multiple anchors. These stated techniques use generally concepts of trilateration and multilateration where three or more signals are analyzed to determine the position of the mobile node. Other alternatives like the Angle of Arrival (AoA), where the angle in which the signal reaches the base station is analyzed. For that, the use of directional antennas is necessary and the analysis of three different signals in order to compute the signals source position. Despite considered less accurate than GPS, many localization methods rely on these techniques, which are called range-based localization methods. Whereas, those that do not depend on measurements are called range-free localization methods [65]. They rely mainly on topological connectivity and cooperative information [66, 67] and typically need a large amount of stationary reference points and extensive communication among neighboring sensor nodes to achieve higher accuracy.

Furthermore, the position of a mobile sensor node (also referred to as unknown node) can also be estimated using estimation-based localization methods. Sequential Bayesian Estimation (SBE), Maximum Likelihood Estimation (MLE), Sequential Monte Carlo localization (SMC), Monte Carlo Localization (MCL), Markov Localization, Kalman Filter (KF), Extended Kalman Filter (EKF), Grid-based Filters, and Particle Filters are examples of localization methods used in MWSNs [68], which are mainly employed to filter the noise to achieve more accurate position estimation. More localization methods designed for MWSNs can be found in [68].

b) Neighbor Location Awareness

In static networks, the locations of nodes do not change; hence, a sole neighborhood discovery performed just after the deployment is generally sufficient to build neighborhood tables that can be used along the network lifetime and serve for routing purposes. However, in mobile networks, nodes' positions change frequently and neighborhood tables become rapidly outdated. Hence, there is a need for nodes to be updated about the locations of their current neighbors especially if a node has a packet to forward. A common approach for updating neighbors on a node's position or general state is that of beacons (commonly known as Hello messages); they are sent either at regular intervals or when a specific event occurs to neighbors. These packets are sent in addition to normal data packets and therefore may incur an extra overhead in terms of processing and transmission. Since nodes are mobile, exchanging periodically beacons between neighbors without packet forwarding (which is generally the case in most of proposed geographic routing protocols) consumes unnecessarily their energy and wireless resources [69]. Moreover, information obtained by long periodic beacon exchanges may become quickly outdated due to the mobility of nodes. This information invalidation becomes higher when the speed of nodes is high. Some few works propose to adopt a reactive on-demand beaconing strategy [69]. On-demand beaconing is of growing importance, mainly in more dynamic and sparse environments (e.g., Delay Tolerant Networks) [70]. Periodic 'on-demand' beaconing has the merit of being generic, thus suitable for use with any existing routing protocol. Given the periodic nature of the beacons, the issue is to select an appropriate beacon interval period, as the value of this parameter has clear implications on the trade-off between performance and signaling overhead (and associated energy expenditure). Indeed, if the beacon interval is very short, the local area around the routed message is burdened with unnecessarily heavy signaling (and the associated energy depletion and bandwidth consumption side-effects), without significant gains in status updates, as it is likely that almost nothing will change from the previous check of the neighborhood. On the other hand, if the beacon interval is very long, the signaling becomes negligible, but the node triggering the beaconing will have a poor perception of its neighborhood and may miss forwarding opportunities, so the routing becomes less effective. The values should be chosen so that forwarding opportunities will not be missed, but also to avoid wasting bandwidth. However, determining appropriate values for the beacon interval did not have received much attention from the research community.

c) Sink Location Awareness

In case of static sink (s), this can be easily implemented in all nodes at the time of sensor deployment. However, when the sink is mobile, nodes should be updated of the new location of the sink. Some geographic protocols assume the availability of a location server. However, considering the mobility of the destination may limit the feasibility of using a centralized location service system. This happens due to the fact that the centralized location system generally needs a long delay to request/reply the real-time location information; thus, the obtained information may be outdated and inaccurate for routing decision [70, 71]. Most of proposed geographic routing protocols with mobile sinks tackle principally the sink location service and differ from each other on how nodes get the location information of the sink. Some routing schemes [72] propose that source nodes flood the network with a sink location query before generating a packet. Other schemes propose that the mobile sink advertises its new location by itself [73, 74]. These solutions range from flooding-based, overhearing-based or delegation-based and mobility-prediction-based solutions [77]. More details about these strategies will be presented in section 5.1.4.

3.2.2 Geographic Forwarding Strategies

In geographic routing, the forwarding strategy consists in choosing as a relay node a node from the neighborhood that fits the best the routing requirements. There are various approaches, such as single-path, multi-path and flooding-based strategies. The most popular forwarding techniques in case of single path are the *greedy forwarding* and the *face forwarding*.

a) Greedy Forwarding

According to the applied greedy rule, the variants of the greedy forwarding are explained through the following figure:

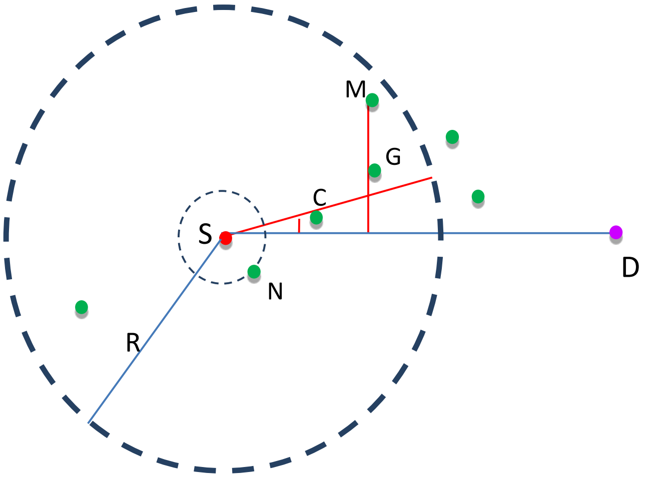


Figure 3: Variants of Greedy Forwarding.

Consider node ***S*** as the source, ***D*** as the destination and other nodes as neighbors of ***S***. ***R*** is being the transmission range of sensor ***S***.

a) *Compass forwarding:* node ***S*** chooses node ***C*** as its next hop since the angle $\widehat{CSD}$ is the smallest angle among all angles formed by neighbors of source ***S***.
b) *Most Forwarding Progress within Radius (MFR):* node ***S*** chooses node ***M*** as its next hop as node ***M*** is the farthest node among the neighbors of source ***S***.
c) *Basic Greedy Forwarding:* node ***G*** will be chosen as the next hop since it is the closest to the destination (the Euclidean distance is a metric of choosing).
d) *Nearest with Forwarding Progress (NFP):* the relay node will be node ***N*** because it is the nearest one to the source.

In the rest of this thesis, we refer to greedy forwarding when applying rule **c**, that is when the next forwarder is selected based on its closeness to the destination using the Euclidean.

b) Face Forwarding

Face (perimeter) routing works on a planarized neighborhood graph (i.e., crossing edges are removed) and packets are forwarded along faces. Face routing has been shown to be correct if the neighborhood graph is connected. In perimeter routing, a message is routed along the interior of faces of the communication graph, with faces change at the edges crossing the ***S-D***-line (red). In figure 4, the final routing path is shown in pink.

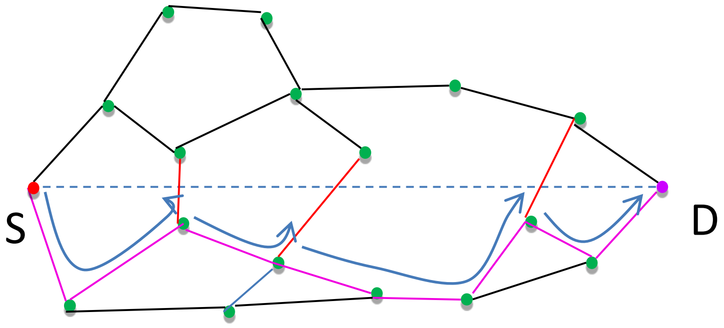


Figure 4: Face Routing.

c) Discussion and issues

Greedy forwarding can lead into a dead end (variously called void or local maximum). This problem occurs when there is no neighbor closer to the destination than the holder of the message. Some protocols such as ***GPSR*** [75] propose to use a combination of the greedy forwarding and the face routing. ***GPSR*** uses the greedy forwarding technique until it fails; then, the face routing can be used to help to recover from that situation and to find a path to another node, i.e. routing around the void until reaching a node closer to the destination than the node that initiated the perimeter. After that, the greedy forwarding takes over. A recovery strategy such as face routing is necessary to ensure that a message can be delivered to the destination [76].

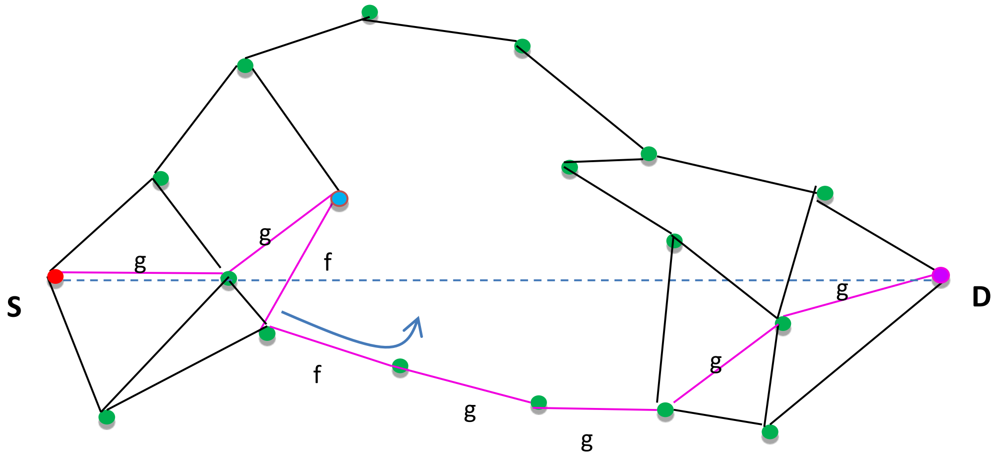


Figure 5: Example of routing with GPSR.

In Figure 5, links tagged with "***g***" are routes found using greedy strategy while those tagged with "***f***" are routes provided using face routing. The example shows that when the blue node falls in local maxima, it initiates a face routing to find a path to another node that is closer to the destination. When such node is found, the greedy routing takes over.

Although perimeter routing theoretically allows recovery from local maximum [78], it is in general much more laborious and consumes more energy of the nodes. Both periodic graph planarization and face routing involve more nodes than greedy forwarding. Furthermore, in the case of low network density, which is common in mobile sensor networks, such a planarization process may fail due to frequent topology changes. Finally, even if a planar graph can be constructed, the potential mobility of nodes may impede face routing by forming an unstable network connectivity graph, ultimately resulting in a degradation of performance or even routing failures.

4. MOBILITY AND LOCATION ERRORS

Two of the most significant factors affecting geographic routing protocols are node mobility and location accuracy [47]. On one hand, mobility can lead to increased overhead due to the number of control messages that must be exchanged before transmitting data (possibly limited to multi/geocast systems) [73]. As well as leading to wrong routing decisions to select the appropriate relay node.

Mobility can affect geographic routing in two ways:

- Fragile connectivity between neighbors
- Out-dated location information

Strongly connected, these two mobility– induced issues can affect each phase of the geographic routing:

- *On location service*: as explained earlier, data routing in geographic routing relies on the knowledge of the node's location, the locations of its neighbors and the destination. However, it is difficult for mobile nodes to keep updated of such information in dynamic networks especially with high mobility scenarios as nodes may move far from the previous stored positions, which lead to routing failure. Geographic routing should deal efficiently with the frequent change of nodes' positions, either those of their neighbors or the sink.
- *On the forwarding strategy*: applying distance-based greedy forwarding in a mobile context is not sufficient as a selected relay may be heading in an opposite direction from the sink. Geographic routing should also consider mobility patterns of nodes when making routing decisions.
- *On nodes' connectivity*: due to mobility of nodes, transmission links between neighbors are susceptible to break at any time. Even if a node identifies successfully its neighbors and chooses the right relay neighbor, if this relay node moves out of the transmission range of the sender before or during data transfer (it means the link breaks), the packet will be lost. Routing algorithms should consider link reliability when making routing decision especially in the case of high mobility of nodes. Moreover, mobility of nodes can cause intermittent connections, isolation of certain nodes, and even the occurrence of local maximum problem. Ignoring such situations leads to routing performance degradation.

On the other hand, geographic routing relies generally on exact positions of nodes, of their neighbors, and of the sink. However, this assumption is unrealistic in real world deployment and location errors are inevitable even when using GPS. Mobility of nodes makes it even harder to get the exact location and may increase significantly the location errors of nodes. In the following section, we present example effects of mobility and location errors on routing decisions:

4.1 EFFECTS OF NODE MOBILITY AND LOCALIZATION ERRORS ON NEXT-FORWARDER SELECTION

Since nodes are mobile (without loss of generality, they can change their directions and speeds, i.e., velocities, at any time), using traditional forwarding strategies such as Most Forwarder within Radius (MFR), Nearest Forwarding Progress (NFP) or Compass Routing (CR) [54] are no longer valid for mobile nodes. Take the example of basic greedy forwarding (GF) widely used in geographic routing. It consists on selecting the nearest to the sink amongst the neighbors. Applied in a mobile scenario, this includes the case where this nearest node is moving in the total opposite direction of the sink or moves with a slower speed compared to its neighbors but has been chosen because at the time of the selection, it was the most adequate according to GF strategy. In addition, nodes are not aware of their exact locations even when using GPS; they can only have estimations and localization errors are inevitable. As a consequence, nodes declared to be close to the sink, in reality may not be. In the following, we present examples of erroneous decisions caused by GF strategy when applied in mobile scenarios.

4.1.1 Effect of Node's Direction

The frequent change in nodes directions may lead to erroneous routing decisions. For example, nodes declared going toward the sink in reality are not and vice versa. The following example shown in figure 6 explains how the node's direction effects routing decisions.

For a source node s, neighbor x_1 is the closest to sink d at time t_0, however, neither x_1 nor x_2 are going towards the sink. Besides, x_3 that seems farther from the sink at t_0 is going toward the sink and at time t_1, x_3 will be the closest one to the sink. Nevertheless, GF strategy chooses erroneously x_1 as the best forwarder of the sender s while in reality x_3 is. As a consequence, packets that should be sent to x_3 will be sent wrongly to x_1 since the sender s believes according to its neighborhood table built at t_0 that x_1 is the best candidate. This problem could be solved in next neighborhood discovery. Yet, the higher the discovery interval, the worse the performance will be.

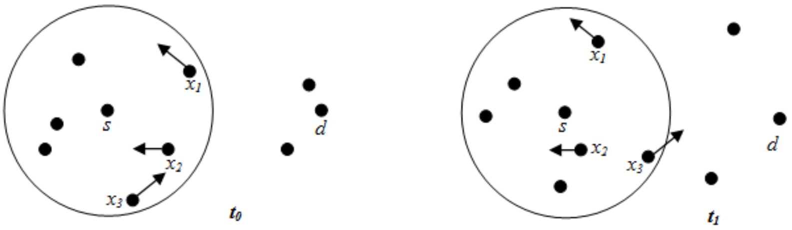


Figure 6: Impact of the direction of mobile nodes on greedy forwarding.

4.1.2 Effect of Node's Speed

Mobile nodes either move with a constant velocity or change it frequently and variably. In the latter case, if the speed is not considered while selecting the best forwarder, a packet may be forwarded to a node that moves with a slow speed. This is because it has been chosen as a forwarder just because at the moment of forwarder selection, it was the closest one to the sink among the neighbors. However, other nodes may not be initially closer to the sink but can reach it quickly and before the assumed best forwarder. Figure 7 provides an example of this case. Sender s has two neighbors closer to the sink than itself: x_1 and x_2. However, x_2 is faster than x_1. At time t_0, x_1 is the closest node to the sink d so it will be chosen according to GF. However, at time t_1, x_2 becomes the closest one.

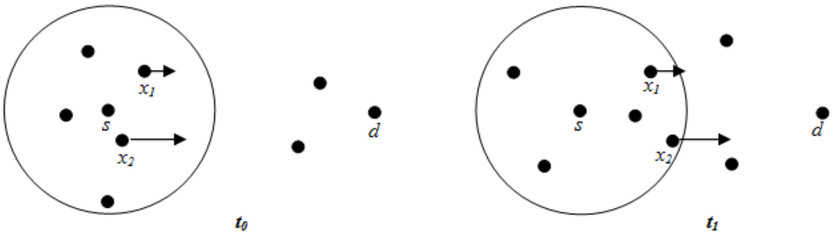


Figure 7: Impact of the speed of mobile nodes on greedy forwarding.

4.1.3 Effect of Localization Error

Geographic routing decision, particularly greedy forwarding, is based on the knowledge of the positions of nodes. However, knowing the accurate positions of nodes and especially of mobile nodes is an unrealistic assumption, and generally impossible in real world deployments. Thus, if a node communicates a wrong position to its neighbors, this can lead to incorrect (non-recoverable) behavior and noticeable degradation of performance [79]. A node believing being nearer to the sink in reality is not and vice versa. Consequently, the routing path may be much longer than what it should be and may result in loops. Figure 8 illustrates an example of the effect of localization error on the next forwarder selection.

Let's consider node ***s*** the current packet holder, x_1 and x_2 are the real positions of its neighbors. x'_1 and x'_2 are their estimated positions communicated to node ***s*** respectively. In light of this information, ***s*** would choose node x_1 as its best forwarder by applying GF strategy since its position estimation is the closest to sink ***d***. However, in reality x_2 is the closest one.

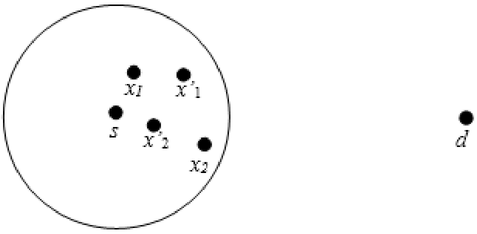


Figure 8: Effect of localization error on forwarder selection.

5. GEOGRAPHIC ROUTING FOR MOBILE WIRELESS SENSOR NETWORKS

In light of the previous issues, in this thesis, we are interested in geographic routing protocols for MWSNs dealing with the aforementioned challenges. For practical reasons, in this chapter, surveyed geographic protocols are organized according to our new taxonomy. Protocols are reviewed based on the Mobility management of nodes namely, Mobility of Sinks and Mobility of Nodes and based on the Location Management (figure 9):

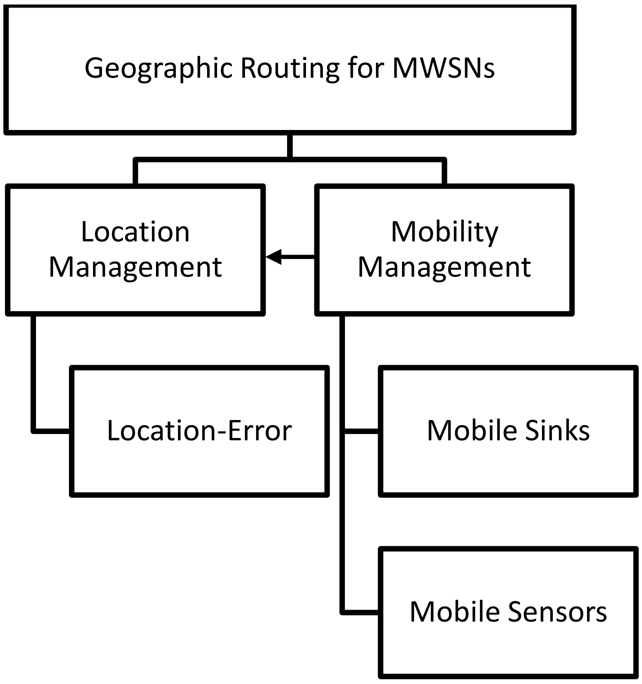


Figure 9: Taxonomy of surveyed geographic routing protocols.

5.1 GEOGRAPHIC ROUTING PROTOCOLS SUPPORTING MOBILITY

With the increasing number of applications that can benefit from MWSNs, there has been a number of routing algorithms proposed in the literature. Nevertheless, there are still no standards for this kind of networks. Depending on mobility on nodes, geographic routing can be divided into:

- Geographic Routing with Mobile Sinks
- Geographic Routing with Mobile Sensors

5.1.1 Motivation of using Routing Protocols with mobile sinks/sensors

Introducing Mobile Sinks and/or mobile sensors into the network is useful for several applications as discussed in the first chapter. In addition to technical advantages that can be summarized as follows:

- ***Connectivity:*** mobile elements can cope with isolated regions. Hence, a spare WSN architecture becomes a feasible option.
- ***Cost:*** the network cost is reduced in a MWSN since no need to the network to be dense.
- ***Reliability:*** mobile sinks can visit nodes in the network and collect data directly through single hop transmissions. This reduces the packet loss and collisions.
- ***Energy efficiency:*** in static networks, neighbors of the sink represent the bottleneck of traffic. Sensor/sink mobility can help in reducing this funneling effect, as their movement can cause traffic to be routed through different regions of the network and spread the energy consumption more uniformly, even in the case of a dense WSN architecture.

5.1.2 Phases of Mobile Sinks/Sensors Geographic Routing

For data delivery to a mobile sink or through mobile neighbors, nodes must go through three phases namely, sink/neighbor location discovery, route construction, and finally the actual data transfer [58-60, 63]. Most of proposed routing protocols in the literature focus on the two first phases with a special attention dedicated to Sink location discovery. In the following, we briefly describe each phase:

- Sink/Neighborhood Location Discovery: In case of mobile sink, sink location discovery is the first step towards reporting the sensed data to a sink. Since the sink keeps on changing its position, nodes need to continuously keep track of the new location of the sink. Often, the sink advertises periodically about its location. The advertisement differs from routing strategy to another. The most common one is by flooding the network. In case of mobile sensors, neighborhood discovery is the first step towards forwarding the sensed data to a suitable relay node. Since the neighbors keep on changing their positions, the packet holder needs to be aware of its current neighbors and their locations.

- Dynamic Route Construction: Upon discovery of the sink/neighborhood, sensor nodes will construct geographically an optimal route to reach the sink. In the case of continuous sink/sensor mobility or high speed, the route construction will be dynamic and the data delivery latency depends on the length of this route or/and local maximum occurrence due to the frequent change of the neighborhood.

- Data transfer: Once a next forwarder is selected, data are transferred to the relay node with the consideration of the reliability of the link between mobile nodes, which keeps on changing subject to the nodes' speeds. Finally, data are delivered to the sink with the goal of ensuring maximum utilization of the contact time with the sink, thereby maximizing the throughput.

5.1.3 Challenges related to Mobile Sink/Sensors Routing

- **Energy issues:** Mobile sinks/sensors alleviate hotspots implicitly since the possible high-energy consumption zones around the sinks shift when the sinks/sensors move. However, the need of frequent advertisement of the sink's location to the network or beaconing between mobile neighbors represents a possible energy drainage. An efficient routing protocol should minimize the overhead of this operation in order to preserve the energy savings.
- **Location errors:** Location errors are often combined with problems arising from unpredictable mobility patterns. Ignoring location errors in routing decisions may lead to wrong transmission since packets may be routed to wrong destinations and as a result the loss of many packets and the cost of communication for rerouting packets.
- **Latency:** The mobile sinks/sensors could be a source of latency in case where the sink's position is unknown to the data generating sensors or the known position of the sink/sensors is outdated. In these cases, sensor nodes should acquire the sink/neighbor position otherwise data will be sent through a longer route leading to a longer latency.
- **Reliability:** if sinks/nodes move during data transfer, data packets that are forwarded during this transfer may be destined to be lost since the sink/chosen relay may not remain within the transmission range of the sender. Successful mobile sink/sensors routing protocols must cope with unreliable links and employ mechanisms to avoid such packets losses.

5.1.4 Review of Geographic Routing Protocols with Mobile Sinks

5.1.4.1 Elastic Routing

Elastic Routing is designed to reduce the communication overhead where a source node has to keep up-to-date the location information of a mobile sink while continuously reporting data to the sink [80]. In Elastic, sensor nodes are static and each sensor can obtain its coordinates via GPS and can obtain information about its one-hop neighbors and their locations via beacons and all sensors have the same disk radio range. Elastic takes advantage of the broadcast feature of wireless transmission. To deal with sink mobility, the new sink's location is propagated to the source node along the reverse geographic routing path via the overhearing mechanism. To achieve this goal, the mobile sink periodically broadcasts beacon messages to announce its current location to its one-hop neighbor nodes. Once the sink moves, it informs the last node from which it received the packet via unicasting. Accordingly, its predecessor on the data path can learn the new location of the sink via channel overhearing. In this way, continuous data packet delivery along the data path enables the source node to learn the most recent location of the mobile sink.

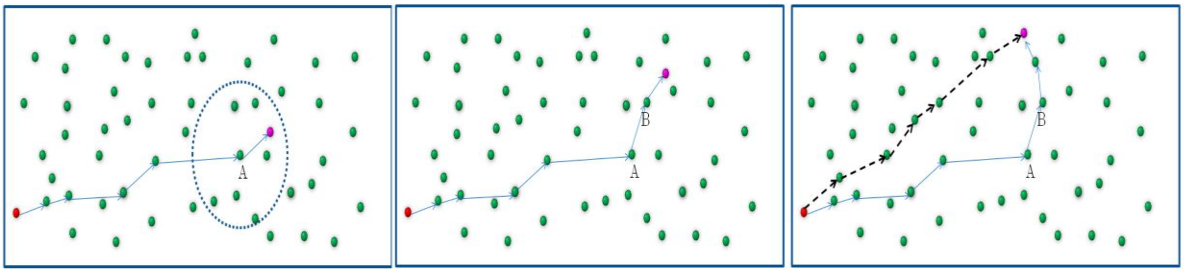


Figure 10: Tracing of a mobile sink in ELASTIC.

Figure 10 shows an example of routing to a mobile sink (in pink) initially neighbor of node A. When the sink moves outside of the radio range of node ***A***, its updates its new location to node ***A***, then ***A*** resets the location of the sink in the next packet to forward and select node ***B*** to be its next hop using greedy forwarding. When moving, the sink sends periodically beacon messages to announce its current location to its new neighbors and to check whether it has moved outrange of the last hop-forwarding node, if so, the sink informs the last hop-forwarding node about its current location by UNICASTING. Then this last node resets the sink new location in the packet it holds, the second last hop-forwarding node overhears the transmission and encapsulates the new location of the mobile sink and changes the sink new location in its upcoming packets, etc, following the reverse path of the source-sink route until reaching the source node (step by step and packet by packet). That way, the source node is kept informed about the location of the mobile sink.

Note that the location learning in Elastic works well with continuous data delivery but can degrade with intermittent data reporting. In addition, transmission channels may be affected by noise since the location propagation of the mobile sink is achieved by overhearing the data transmissions. Thus, nodes may not hear an accurate location of the sink, which may lead to increased packet loss.

5.1.4.2 EERPM- Energy Efficient Routing using Mobility Prediction

EERPM [81] was designed to route packets to a mobile sink using mobility prediction. Authors assume that the source and all sensor nodes are located at fixed and known positions and the mobile sink can estimate and track its location, speed, and acceleration with a Kalman filter.

This method is presented for efficiently and reliably routing data packets from a static information source to a mobile sink through a multi-hop wireless sensor network. To reliably and timely route data packets, the source predicts the location of the mobile sink. The prediction is updated by receiving messages from the mobile sink, containing its current location, speed, and acceleration. These messages are sent only if the

Euclidean norm of the error between the predicted state and the state estimated by the *Kalman Filter* exceeds a pre-defined threshold. The control messages and the data packets are forwarded in a multi-hop fashion through the network using geographic greedy forwarding.

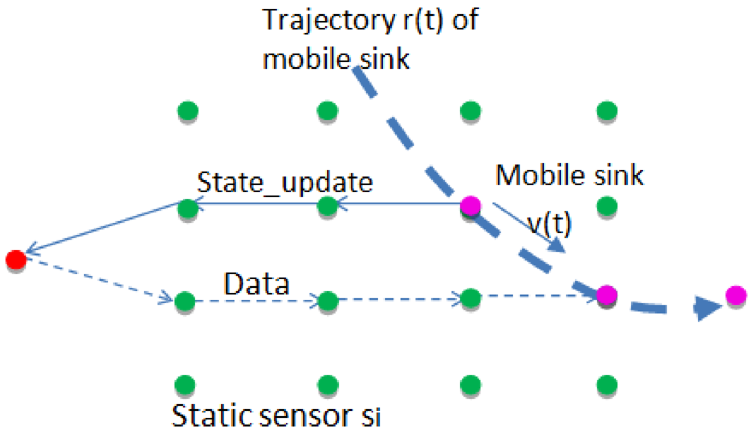


Figure 11: Mobile sink moving in a static sensor field [81].

Figure 11 shows an example of a mobile sink updating its state to the source node and based on this state; the source sends data to the predicted location of the sink.

While the idea of predicting the new location of the mobile sink is very efficient and time saving, location errors resulted from the prediction are not considered.

5.1.4.3 ALURP- Adaptive Location Update Routing Protocol

Avoiding flooding the sink location in the network by informing only a small adaptive area is the basic idea behind of ALURP routing [82]. In ALURP, only the sink can move and each node knows its geographic location and its 1-hop neighbors' locations.

Initially, the sink resides at the virtual Center (VC) and the radius of the circular adaptive area is 0. When the sink moves farther away from the point VC, the radius increases and the sink needs to update its location in this adaptive area. The adaptive area is constructed as the circle (VC, $D_{vc,sink}$), where VC is the virtual center and $D_{vc,sink}$ is the distance between the VC and the current location of the sink as shown in figure 12. Note that whenever the sink moves, the VC becomes the old position of the sink.

The data source can send the packet toward the point VC until the packet meets any node in the adaptive area who knows where the sink is located. This node is called "Dissemination Node" DN, after that, DN forwards the packet to the new location of the sink via greedy forwarding.

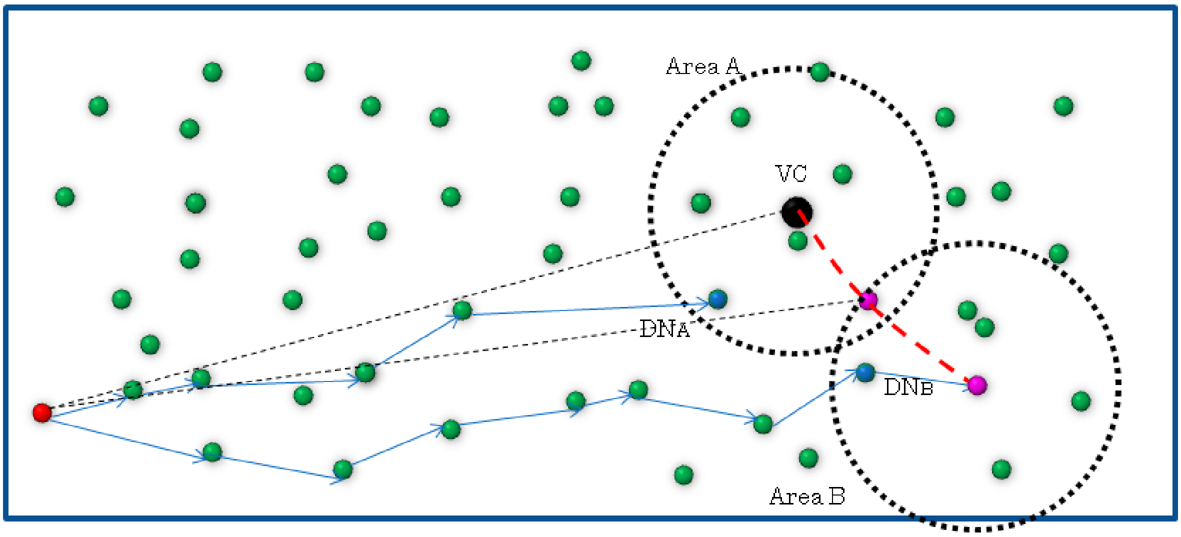


Figure 12: Adaptive Area in ALURP [82].

ALURP saves energy by keeping communication with sensors and sink local thanks to the adaptive area. However, In case of low mobility, DN may excessively consume energy, because data are always sent to the DN instead of the sink. Also, the choice of DN node seems to be arbitrary. Another issue with ALURP is that if the destination area is too small and the sink changes frequently its position, this leads to excessive energy consumption and overhead resulted from updating the routes. Moreover, it is true that the frequency of the global flooding of the sink location decreased but at the expense of increased data delays caused by the usage of suboptimal routes to the sink. Note that ALURP considers the issue of routing only to one mobile sink.

5.1.4.4 Predictive QoS routing to mobile sinks

To ensure uninterrupted data delivery to a mobile sink, a mobility prediction based scheme in proposed in [84]. The proposed scheme delivers sensory data to a mobile sink via relay nodes that are predicted based on a mobility graph of the mobile sink. The mobility graph is pre-computed based on a sequence of those nodes that receive relatively strong RSSI signals from the mobile sink. Each time, when the mobile sink moves from one relay node to the next, it floods the network with the information of the next predicted relay node and arrival time. The prediction is used to compute new routing potentials before the old routes become useless. The prediction algorithm calculates the similarity of the current trip to the past trips and returns the closest match. This helps sensor nodes to dynamically adjust their routes with the predicted next relay node in accordance with anticipated arrival time of the mobile sink. To keep updated about the location of the mobile sinks, at each movement of a sink, the information potential has to be adapted to the new location of the sink. In practice, each relay node stores and updates two potential functions:

- The current potential used for routing.
- The predicted potential is used once the transition to the predicted node took place.

Figure 13 shows the mobility graph and the connectivity graph that help to predict the relay nodes.

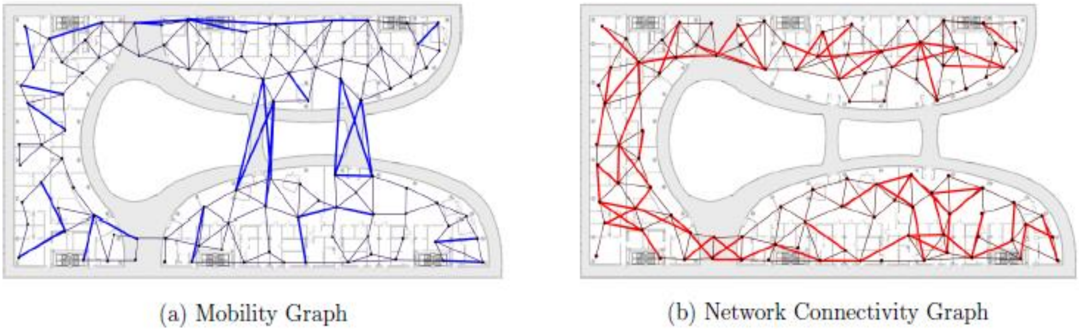

(a) Mobility Graph
(b) Network Connectivity Graph

Figure 13: Difference between Mobility and Connectivity graphs. Blue edges represent regions where no coverage is, red edges represent areas where movement is constrained by walls [84].

The Prediction is proven to be energy efficient and the reported experimental results reveal high packet delivery ratios at low speeds of the mobile sink which gradually degrades as the speed increases. However, the continuous update of the two potentials (current and estimated) leads to data latency and overhead. In addition, all traffic data are forwarded to the relay node, thus, it will be bottleneck. Furthermore, the proposed scheme considers sink mobility in an indoor office environment where the mobility is relatively constrained and thus easier to predict compared to an outdoor scenario.

5.1.4.5 ILSR-Integrated Location Service and Routing

ILSR [83] aims in guarantying the packet delivery to a mobile sink by maintaining a slow-varying routing to the sink. As previous protocols, ILSR assumed that nodes are aware of their own geographic position through GPS and of their 1-hop neighbors via “hello” messages. The mobile sink initially floods the network (once) with its location information and throughout the process remains connected via at least one node from that network. The sink moves slowly such that neighborhood change is detectable. To incorporate sink mobility, in ILSR, the sink location-update message is additionally routed to some selected nodes for prevention from routing failure. By using both of “uncontrollable (UM)” and “controllable (CM)” sink mobility, data delivery is guaranteed in a connected network modeled as a unit disk graph (see Figure 13). ILSR uses the Geographic Forwarding Graph (GFG) routing technique [85]. Thus, ILSR for Mobile sinks is considered as GFG plus an integrated location service which is decomposed into *flooding-type* and *routing type*. The flooding-type is restricted only within the area near the sink in which the nodes detect some change in the next-hop node route towards the sink while the second type is engaged to prevent routing failures in the network. Both these location update messages are time-stamped via a monotonically increasing sequence number for maintaining freshness. ILSR reduces the message cost by dynamically controlling the level of location update. However, this scheme is only applicable for delay tolerant applications because of the long convergence time for route adjustment in the case of sink mobility.

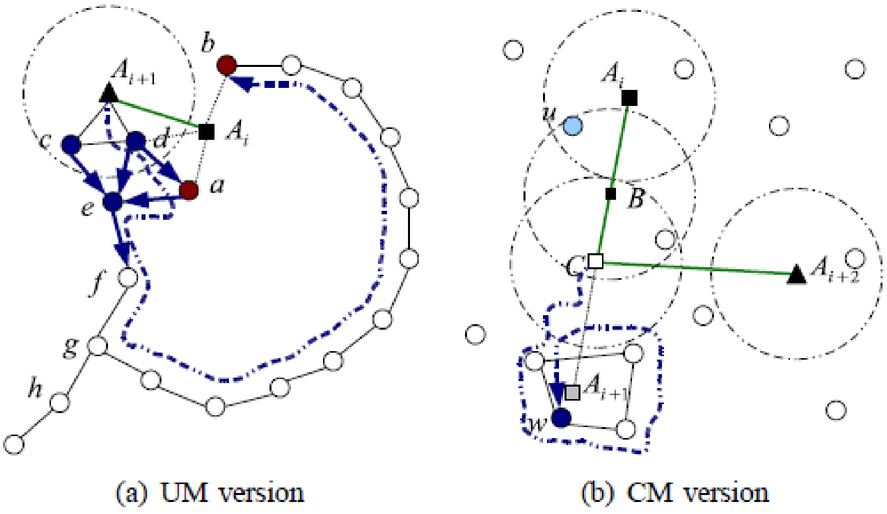


Figure 14: Sink Location update in ILSR [83].

5.1.2 Review of Geographic Routing Protocols with Mobile Sensors

5.1.2.1 GPSR

Greedy Perimeter Stateless Routing (GPSR) [75] is a well known geographic routing protocol that combines the two different forwarding strategies: greedy forwarding and perimeter-right hand rule (face routing). GPSR uses first greedy forwarding approach by using only neighborhood information. When greedy forwarding becomes impossible (if a packet arrives at a dead end), then the forwarding strategy switches to face routing, where the packet is forwarded along the FACES of the planar graph. The use of planar graphs is an alternative strategy for recovering from the local maxima problem. However, in mobile scenarios, planarization generates additional issues and cannot cope with all mobility scenarios. In addition, GPSR is based on simple greedy forwarding without taking into account the mobility pattern characteristics of nodes; which may lead to wrong decisions as explained in section 4.1. GPSR results in large number of beacons to maintain routing table which results in communication and processing overhead. GPSR performs well in dense networks where the average network degree is greater than 20 but performance deteriorates with the decrease in the density of networks.

5.1.2.2 GPSR-MS

GPSR-MS (GPSR with Mobile Sensors) has been proposed in [86]. GPSR-MS proposed a mobility-based forwarding mechanism to a static sink. In GPSR-MS, all mobile nodes are aware of their locations and speeds via GPS. For neighbors' discovery, each sensor node broadcasts periodically a 1-hop location beacon informing its neighbors about its geographic position and speed. Based on this exchange, nodes build a neighboring table from which the next forwarder will be selected. To select the next forwarder, authors propose to consider also the metric of the speed of the moving node in the greedy forwarding. Hence, the next-forwarder objective function calculated by the current sender ***s*** for each neighbor ***i*** is expressed as follows:

$OF_i = \frac{DT(i,d) * Dir(i,d)}{Speed\ (i)}$ where *DT (i,d)* is the previous distance between node ***i*** and destination ***d*** stored in the neighboring table of ***s*** while *Speed (i)* is the moving speed of ***i***. *Dir (i,d)* is considered by ***s*** as the direction of node ***i*** and is calculated as:

$Dir\ (i,d) = \frac{DT\ (i,d)}{DB\ (i,d)}$ where *DB (i,d)* is the new distance between node ***i*** and ***d*** communicated by node ***i*** to ***s*** during beacon exchanges. Authors consider node ***i*** a static node if *Dir (i,d)* is equal to 1. If *Dir (i, d)* is greater than 1 then node ***i*** is approaching ***d*** while if *Dir (i,d)* is less than 1 then ***i*** is moving away from ***d***. Sender ***s*** chooses according to its neighbors' table the node having the smallest objective function as its next forwarder.

Considering the moving speed in the forwarding mechanism is of a paramount importance in MWSNs. However, the proposed objective function does not cover all the motion possibilities of nodes. For instance, a node is considered static when its current distance to the sink is the same as the one calculated in the previous timestamp while in reality the node might just moved with the same distance as shown in figure 15. This assumption jeopardizes the reliability of the used objective function. A study on the effect of mobility patterns is also crucial but has not been considered by authors.

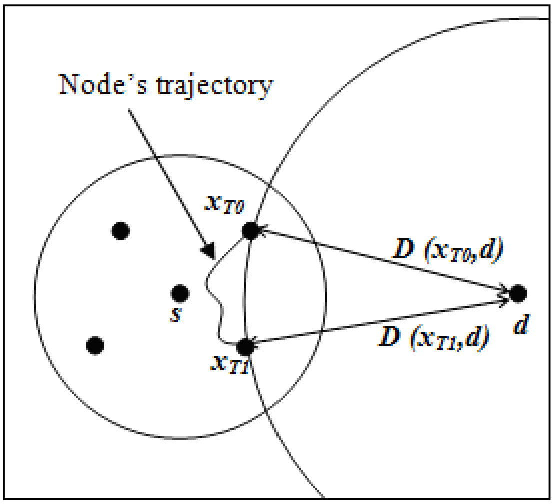


Figure 15: Node moving with same distance from destination.

5.1.2.3 PAGER-M

Le et al. [87] proposed the PAGER-M algorithm, which utilizes the location information of the sensor node and the sink to assign to each sensor node a cost, which is close to the Euclidean length of the shortest path to the sink. Authors consider a static sink that has a communication range long enough to cover all the nodes in the network. A packet is forwarded to the sink using greedy forwarding whenever possible. When a packet reaches sensor nodes near a local maximum, and where greedy forwarding will be impossible after a number of hops, the packet is forwarded following the high-cost-to-low-cost rule. This rule helps to reduce the transmission failures caused by mobility. The sending node chooses the closest and safest neighbor in terms of link reliability. Due to the long beacon broadcast interval of PAGER-M, the routing overhead is significantly lower. However, PAGER-M considers mobile nodes with long pause time, which does not help situating the protocol in highly dynamic networks, and with continuous moving nodes.

5.1.2.4 M-GEOCAST

M-Geocast [88] considers the case of GPS-enable mobile sensor network where any node can move and have its location anytime. It is designed in such a way that when there are multiple sinks, one of the sinks is selected as a master sink. The master sink acts as a location service provider and data collector and dissemination server. The other sinks only intimate to the master sink about their locations using a Unicasting. All nodes send their data to the master sink and in turn it forwards the data to the other sinks. M-Geocast utilizes simple geographic forwarding to send messages to the master sink. As for location information of nodes, each node gets the location information of all its neighbors through neighborhood discovery process. In the neighborhood discovery process, each node periodically broadcasts its location information to its neighbor using a MAC level broadcast including its own identifier. When a neighbor node hears a beacon, it generates its beacon just once to inform its location to the newcomer. This allows each node to keep track of their neighbor's location even during movement while suppressing the unnecessary beacon transmissions. Location information of the master sink while on movement is propagated throughout the sensor field by periodic flooding. To overcome the local maximum problem, M-Geocast tries first to discover a second path to the destination by using the path history of the location updates. This is called *path history forwarding*. Second, if both the geometric routing and path history forwarding fail either due to a routing hole or due to a broken link, M-Geocast can discover a new path to the destination on demand by flooding the network with a *route request* message as in reactive routing protocols thus relying on non-geographical strategy. Figure 16 shows an example of M-Geocast routing in case of two sinks.

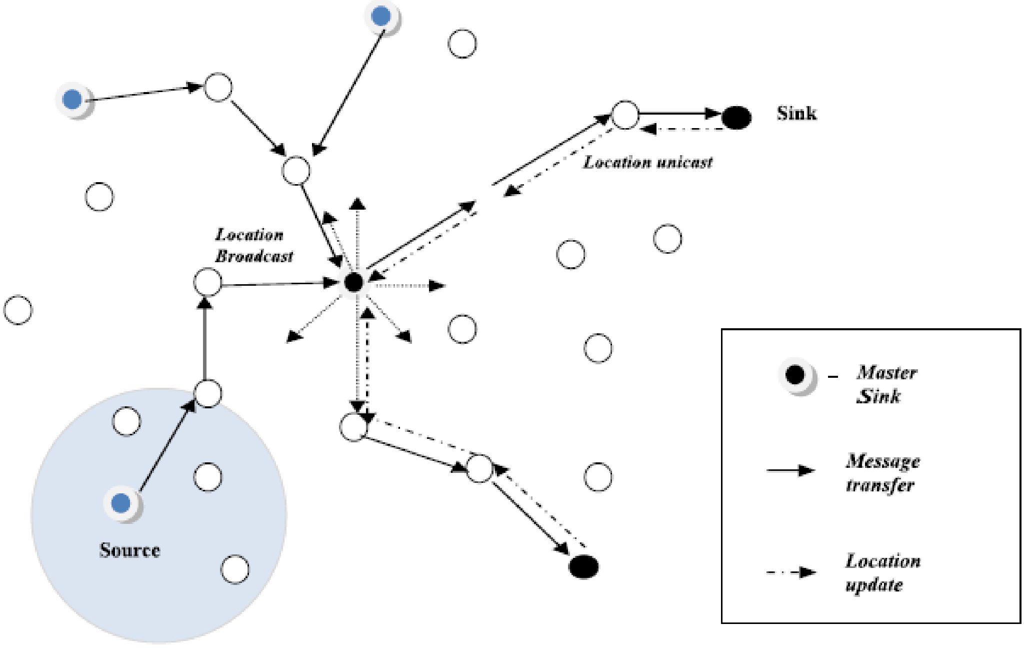


Figure 16: Routing through a master sink in M-Geocast.

It is pragmatic from the simulation results of [88] that M-Geocast's packet delay remains stable even when the nodes' speed increases as long as the location information of the destination remains valid. However, all the traffic of the network passing by the master sink can cause a real bottleneck causing high packet latency or packet drops.

5.1.2.5 MAGF

A refined next-hop selection rule named Mobility-based Adaptive Greedy Forwarding MAGF was proposed in [89] in which authors came up with a concept named *motion potential* that combines node position with mobility patterns to select the next-hop forwarder. Authors assume that the mobility pattern and the locations of nodes are supposed to be known beforehand thanks to GPS. The neighbors of a sender node are divided into two regions (see figure 17) namely the *progressive region* in which the selection is exactly as greedy forwarding and the *potential region* (behind the sender) where a motion potential function is applied to select the best forwarder without using face routing. It is worth to mention that the forwarder selection process from the progressive region is used whenever possible and the potential region is used as an alternative if there is no node in the progressive region thus no node closer to the destination than the forwarder (local maximum situation). Figure 17 shows how neighbors of the packet holder are divided into progressive region (lined area) and potential region.

Formally the two regions are defined as follows:

Progressive Region = $\left\{(x,y) \,\middle|\, d\big((x,y),N_d\big) < d(N_i,N_d)\ \&\ d\big((x,y),N_i\big) < \ N_i < r(N_i)\big)\right\}$ *and*

Potential Region = $\left\{(x,y) \,\middle|\, d\big((x,y),N_d\big) \geq d(N_i,N_d)\ \&\ d\big((x,y),N_i\big) < \ N_i < r(N_i)\big)\right\}$

where *d (a,b)* represents the distance between points *a* and *b*, and r(*Ni*) is the communication range of node *Ni*.

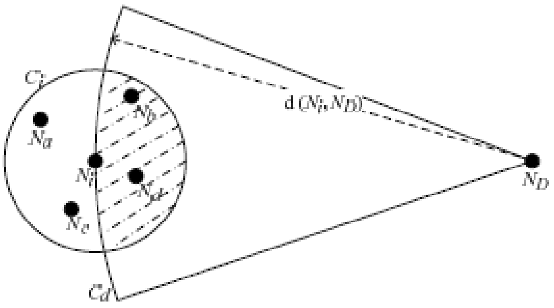


Figure 17: Progressive region and Potential region.

If greedy forwarding from the progressive region failed, the motion potential function is applied as an objective function to select the next forwarder from the potential region. The function considers the speed of mobile nodes and the angle they form with the destination. In case the packet holder fails to find a forwarder from the two regions, it carries the packets for a determined time. If this time elapsed before finding a forwarder, the packet will be dropped.

Exploiting the mobility patterns together with the carry-and-forward strategy is a promising idea especially in delay-tolerant networks and intermittently connected networks. However, neither the speeds, nor the directions of nodes are considered in the progressive region.

5.1.2.6 LASER

Location aware sensor routing (LASeR) protocol was proposed in [90] for MWSNs where authors assume mobile nodes with perfect localization. The protocol uses location information to maintain a gradient field in mobile environments. As for the forwarding strategy, it applies a *blind forwarding* where no specific forwarder is selected but instead a transmitting node broadcasts the packet along with its distance from the sink. The transmitting node's neighbors then overhear this broadcast and then decide whether to forward the packet or not, by comparing the transmitting node's distance from the sink with their own. Thus, the protocol inherently utilizes multiple paths simultaneously to create route diversity. However, this means there may be more than one receiving node, in which case there is a high chance that multiple nodes will reply with acknowledgments (ACK). The multiple ACKs are likely to collide, which means ACK will not be received by the sender node and could cause the packet to be retransmitted unnecessarily creating congestion in the network.

5.1.2.7 AeroRP

Envisioning for Aeronautical Networks (ANs), AeroRP was proposed in [91] and its improvement in [92] where mobile nodes are assumed to be aware of their locations, their moving speeds and directions. AeroRP selects the relay node to forward the message, by jointly considering distance and moving direction as well as speed. As the example shown in Figure 18, the metric Time-To-Intercept (TTI) for node A to approach destination D is calculated as $TTI_{A,D} = Dist_{A,D}/(Speed_A \times \cos \phi_{A,D})$, where $Speed_A$ is the current moving speed of node A.

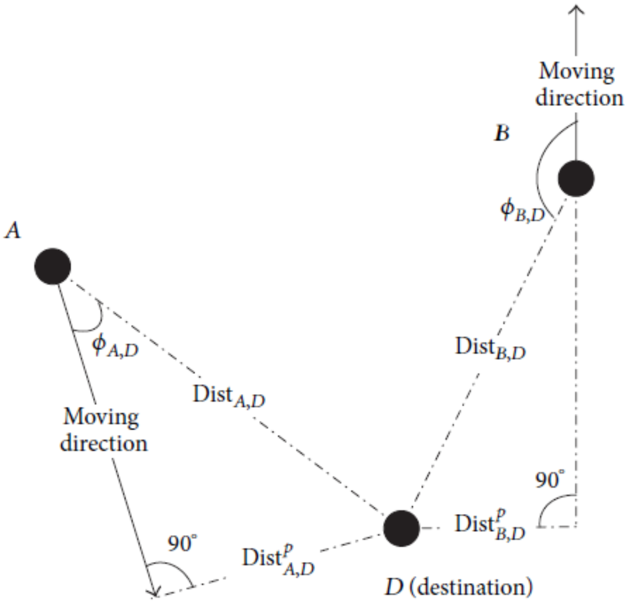


Figure 18: Illustration of geometric policy in AeroRP and TBGR.

If there is no neighbor better than the packet holder in terms of TTI (that is, falling into a local maximum situation), then the packet holder chooses between three modes whether to carry the packet, buffer it or drop it. The protocol is delay-tolerant since aeronautical vehicles fly with high speeds which can cause intermittent connections.

Since AeroRP only considers the case when neighbors are moving towards the destination, its forwarding strategy is limited in case the packet holder is moving away from destination even if its encountered node is moving towards destination. Here, according to its forwarding strategy, the message will not be forwarded. This is because the negative value of TTI is invalid for making routing decision. Due to the very sparse network density and high speed in ANs, failing to forward a message due to such limitation degrades routing performance.

5.1.2.8 TBGR

A routing scheme called The Best Geographic Relay (TBGR) was proposed in [93] for DTNs. Authors assume that GPS is available for all mobile nodes in the network. The location of the stationary sink is available for all mobile nodes. Although authors acknowledge the effect of location error on the routing decision but proclaim that their scheme is still applicable giving such obstacle. In TBGR, messages are usually with a certain lifetime, evaluated as Time-To-Live (TTL). Within a message lifetime, a limited L number of copies, including (L − 1) replicated copies, and together with the original message will co-exist in a network, such that at least one of them can be successfully delivered to the sink. Otherwise, the message will be discarded until TTL expires. As for the forwarding strategy, similarly to AeroRP, a Utility Metric is calculated as:

$$UM_A = Dist_{A,D} - R/(Speed_A \times \cos \phi_{A,D}) \quad (1)$$

This metric intends to capture the time for A to intersect D given a fast moving speed $Speed_A$. Neighbor A is selected as a relay if it satisfies the following condition:

$$(UM_S > UM_A) \text{ and } (\cos \phi_{A,D}) < \pi/2 \quad (2)$$

Where UMs is the utility metric of the current packet/copy holder.

It is functional to duplicate the message to increase the chance of its delivery to the destination. However, the presence of multi-copies in the network needs a well-developed buffering strategy. In addition, authors assume that a node encounters only one neighbor while encountering multiple nodes at once is not investigated.

5.2 GEOGRAPHIC ROUTING PROTOCOLS WITH LOCALIZATION ERRORS

Most of geographic routing protocols assume that each sensor knows its exact position by enabling GPS localization or other localization methods [94]. However, in practice, localization methods do not provide accurate positions for all sensors. In the study of [95] authors presented an energy consumption analysis of geographic routing with location errors and concluded that poor localization is the main reason for energy wastage since more power is spent on both the successful and less successful packets. Authors observed also that the percentage of packets that are dropped due to location error is higher than the percentage for other reasons. Hence, ignoring location errors in routing decisions may lead to wrong transmissions since packets may be routed to wrong destinations and as a result the loss of many packets and the cost of communication for rerouting packets. Thus, an efficient geographic routing protocol should consider these location errors while making routing decisions.

5.2.1 Sources of Localization Error

We identify at least five main sources of localization error in MWSNs:

1) Measurement
2) Finite precision
3) Uncertainties in anchor locations
4) Mobility
5) Localization algorithms.

The first two, measurement and finite precision-related errors are inherent in all physical computing systems. Measurement errors arise due to sensing technology limitations, phenomena instability, and noisy environment [96]. Numerous well studied techniques exist to reduce or compensate such errors in many domains. Finite precision errors are the result of inaccuracies induced due to limited computation precision of digital computers. Since the WSN hardware is typically very resource constrained, such errors can be of significant importance [97]. The third source of location errors is due to uncertainties in anchor (s) locations in case where the localization strategy relies on receiving location beacons from anchors. Mobility of nodes can affect significantly the localization process as explained in section 4.1. The efficiency of localization algorithms has also a considerable impact on the location accuracy and the amount of resulted error. In fact, the choice of the used measurement technique, the geometric calculations, the used probabilistic approach, or the location refinement in case of error propagation in multi-hop localization can all influence the accuracy of the localization algorithm [98].

5.2.2 Localization Error Modeling

The localization error of node ***i*** is defined as the distance between the estimated position and the real position of ***i*** and is calculated as: $\varepsilon_i = \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2}$ (3)

Where (x_i, y_i) is the real position of ***i*** and $(\hat{x}_i, \hat{y}_i)$ is its estimated position.

In static networks, most of works concerned by location errors tackled only measurement-induced errors. These works assume that the location error in each node is independent and is generally modeled by a Gaussian distribution $N(\mu, \sigma^2)$ with zero mean $(\mu = 0)$ and finite standard deviation σ [94, 95, 99]. The variance of the Gaussian error on x-axis and y-axis for each individual node are assumed to be equal. The Gaussian probability function is given by:

$$f(x) = \left(\frac{1}{\sqrt{2\pi\sigma^2}}\right) \exp\left(-\ \frac{(x-\mu)^2}{2\sigma^2}\right) \tag{4}$$

The error ε_i of node ***i*** follows a Rayleigh distribution [100] with probability density function:

$$f(\varepsilon_i) = \frac{\varepsilon_i}{{\sigma_i}^2} e^{-{\varepsilon_i}^2 / 2\,{\sigma_i}^2} \tag{5}$$

As a consequence, the distance between two neighbors is also subject to localization error. Let ***i*** and ***j*** be two neighbors, $d_{ij}$is its accurate distance calculated as $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ and $\hat{d}_{ij}$ is their estimated distance. $\hat{d}_{ij} = \sqrt{(\hat{x}_i - \hat{x}_j)^2 + (\hat{y}_i - \hat{y}_j)^2}$ where $(\hat{x}_i, \hat{y}_i), (\hat{x}_j, \hat{y}_j)$ are the estimated positions of ***i*** and ***j*** respectively. The probability density function of $\hat{d}_{ij}$ follows a Rician distribution [94] and is given by:

$$f(\hat{d}_{ij}) = \frac{\hat{d}_{ij} e^{-(\hat{d}_{ij}^2 + d_{ij}^2)/2\sigma_{ij}^2}}{\sigma_{ij}^2}\ I_0\left(\frac{\hat{d}_{ij} d_{ij}}{\sigma_{ij}^2}\right) \tag{6}$$

Where $\sigma_{ij} = \sqrt{{\sigma_i}^2 + {\sigma_j}^2}$ and $I_0(x)$ is the modified Bessel function of the first kind and zero order given by:

$$I_0(x) = \frac{1}{\pi} \int_0^{\pi} e^{x\, cos\theta} d\theta \tag{7}$$

The mean (expectation) of the estimated distance $\hat{d}_{ij}$ is

$$E(\hat{d}_{ij}) = \sigma_{ij} \sqrt{\frac{\pi}{2}}\, L_{\frac{1}{2}}\left(-\frac{d_{ij}^2}{2\sigma_{ij}^2}\right) \tag{8}$$

Where $L_{\frac{1}{2}}(x)$ denotes the Laguerre Polinomial given by:

$$L_{\frac{1}{2}}(x) = \exp\frac{x}{2}\ \left[(1-x) I_0\left(-\frac{x}{2}\right) - x\, I_1\left(-\frac{x}{2}\right)\right] \tag{9}$$

And I_1 is the modified Bessel function of first kind and first order.

The variance of the estimated distance $\hat{d}_{ij}$ is:

$$Var\left(\hat{d}_{ij}\right) = 2\,\sigma_{ij}^2 + d_{ij}^2 - \left(\frac{\pi\sigma_{ij}^2}{2}\right) L_{1/2}^2\ \left(-\frac{d_{ij}^2}{2\sigma_{ij}^2}\right) \qquad (10)$$

However, in mobile networks, few works considered the location errors, mainly GPS-induced errors. For example, Kasana et al. [101] proposed the same previous model for vehicular networks where each vehicle is equipped with GPS receiver while works using mobility prediction used simulation to deduce then a location error model [102-104]. With GPS-free localization, modeling the localization error becomes even a very complex task as it depends on many factors including the aforementioned sources of location errors. In addition, a mobile node's location error is inconsistent due to its dynamic mobility, which makes it harder to predict/mitigate [47].

5.2.3 Review of Geographic Routing Protocols considering Localization Errors

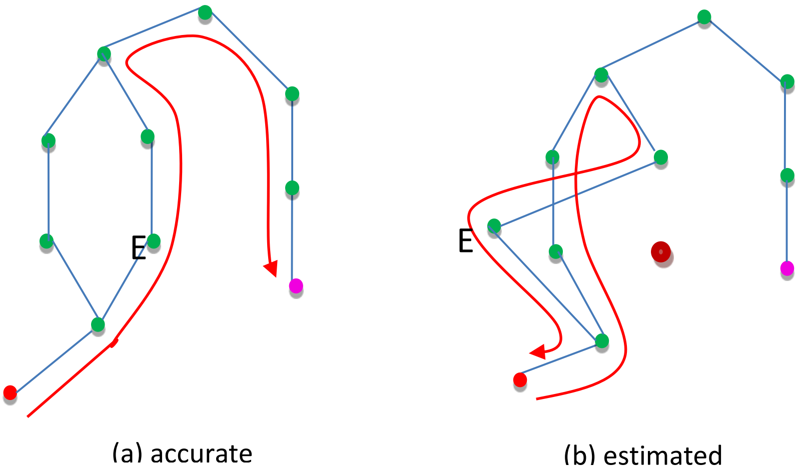
In this section, we will present some geographic protocols that consider localization errors.

5.2.3.1 On the effects of Localization Errors on Geographic Face Routing

The work in [79] provided a detailed analysis of the effects of location errors on the correctness and performance of geographic routing in static sensor networks. To do so, authors assume that each node knows about its neighbors and their locations. The network is assumed to be static and stable (i.e no motion and no failures). No obstacles in the sensor field and nodes have consistent information about other nodes. Authors presented a detailed micro-level analysis of pathologies for geographic face-based routing protocols in the presence of location errors. They adopt a novel approach in synthesizing the error scenarios. Starting from the planarization algorithms, they establish completeness conditions and bounds for errors. Authors decompose geographic routing into three main components and analyze the effect of location error in each component namely, Greedy forwarding, Planarization and Face routing. Since failures of greedy forwarding are recovered by the face routing, authors focus their study on persistent protocol failures caused by failures in Face routing. Authors deduced then that Face routing failures are strongly associated with planarization failures.

According to this micro-level analysis, authors categorize the problems that cause face routing failures into three main categories:

- Edge removal causing disconnection.
- Cross links as shown in figure 19.
- Inaccuracy in the destination's location.



(a) accurate (b) estimated

Figure 19: Cross links causing Face routing failure [79].

The analysis identified *information hiding* -that it, when one of the nodes cannot get the information to construct a correct planar graph- as one of the main causes for incorrect (non-recoverable) behavior. They then provided a simple fix for this error based on information sharing among the nodes during planarization. Simulation case studies (for GPSR [75] and GHT [105]) are conducted to quantify the effect of location errors on protocol performance and to validate the efficacy of the proposed modification. The results show that even for realistic and relatively small location errors, the effects of location errors are noticeable. For example, in GHT more than 10% of sensor network events storage can fail in the presence of a location error of 10%. Whereas, when the location errors are considered, the enhanced versions gave better results.

This work represents the first detailed micro-level analysis of pathologies for geographic face-based routing protocols in the presence of location errors. However, the analysis is done only for static and stable networks.

5.2.3.2 ELLIPSE Routing Protocol with Uncertain Positions

Ellispe [106] was proposed in order to reduce the number of messages in the network by using a region-based routing. In Ellipse, the network is composed of static nodes where all nodes are aware of their location errors. If ε_u is the location error of node ***u***, so, the real position would be inside a disk centered in (x_u,y_u) with radius ε_u. The position (x_d,y_d) of the destination is known by all the sensors and all sensors know the ellipse factor *"l"* before deployment. The Ellipse region is defined by an ellipse form built knowing the source position, sink position, distance between them and the ellipse factor. Only nodes in the ellipse region forward messages. Before sending a message, the source includes its position (x_s, y_s). When sensor *"u"* receives a message, it checks whether it is inside the ellipse or not the following formula:

$\boldsymbol{D_{su}} + \boldsymbol{D_{ud}} <= \boldsymbol{l} \times \boldsymbol{D_{sd}}$ where ***l***: ellipse factor and D_{sd}: distance between source and sink.

All nodes in the ellipse region and those who receive messages, forward it with a probability *"**p**"*. Probability *"**p**"* defines a sub-set of nodes which will relay messages towards the destination. Eg. if ***p* = *0.5*** then, half of sensors in the ellipse will be relay nodes. Note that neighbors of source and sink always forward messages even if they are out of the ellipse. This is to ensure that even if the source and sink are not accurately located; the message can be sent and can be received.

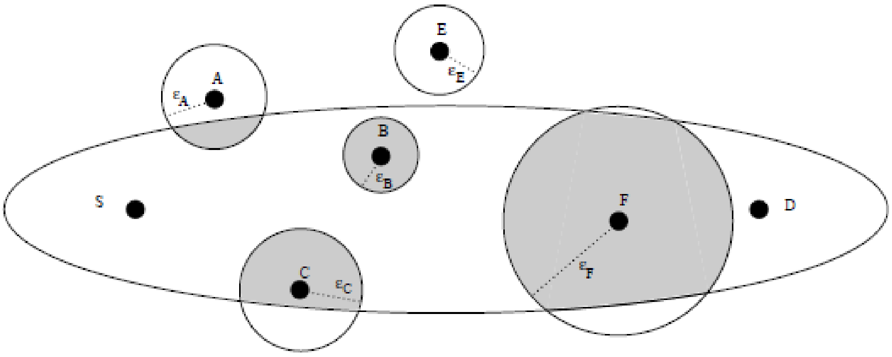


Figure 20: A network with Localization errors in Ellipse [106].

To determine to how many hops a message should be forwarded (for example. If the number of hops $\boldsymbol{h}$=1, then, all 1-hop neighbors can be relay nodes), authors propose to calculate the minimal number of hops to reach sensors close to ***S*** is the ceiling of $\frac{\varepsilon}{r}$. To avoid dropping messages, h >= $[\frac{\varepsilon}{r}]$ +1.

To determine if a node is inside the ellipse and thus can be a relay node, each potential relay node can calculate its probability to be inside the ellipse with $P_A = \frac{A_A}{\pi\varepsilon_A^2}$ where $\boldsymbol{A_A}$ is the intersection of the circle of ***A*** and the ellipse (grey area in Figure 20) and ε_A is the bound error of node ***A***.

One of the advantages of Ellipse routing is that there is no need for a sensor to know the positions of its neighbors since the packet is flooded inside the ellipse. However, Authors did not focus on the broadcasting strategy inside the ellipse. In addition, the condition that all nodes in the ellipse forward the packet can lead to packet replications and network congestion due to the unnecessary involvement of many relay nodes in the routing process.

5.2.3.3 ALBA-R

ALBA-R protocol was proposed in [107, 108], a localization error-resilience geographic routing based on nodal coloring mechanism for handling nodal connectivity holes called Rainbow [108]. Rainbow mechanism is used to handle local maximum situations as an alternative to face routing to avoid network planarization. A fixed error is injected for each node. The forwarding mechanism considers only the estimated distance between a node and a sink to divide then the transmission area of the packet holder $\boldsymbol{x}$ into two regions namely $\boldsymbol{F}$ and $\boldsymbol{F_c}$ (see figure 21). Nodes belonging to region *F* are always colored in yellow, meaning that a route until the sink is possible unless a node falls in a local maximum. In this case, the node changes its color to red and considers nodes in F_c as candidates. A switching of color is then proceeded depending on the ability for a neighbor node to candidate in forwarding the packet or not.

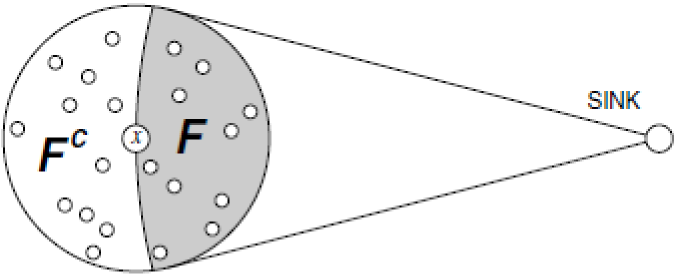


Figure 21: Forwarding regions of node x in ALBA-R.

Authors stated that their protocol is totally error-resilient even when the location error is twice the transmission range but they provided no error calculation method. Note that the proposed protocol did not consider the mobility of nodes or the mobility of the sink.

5.2.3.4 MER- Maximum Expectation within Transmission Range Geographic Routing in the presence of Location Errors

Developing a location error model and considering the impact of location errors on geographic routing in multi hop wireless networks are the main objectives of the work in [109]. To do so, authors assume a set of assumptions about the wireless network:

- All sensors are equipped with GPS to measure their locations.
- Location errors of different nodes are independent, and are proactively broadcasted.
- The location error at each node is modeled by Gaussian distribution with zero mean and finite deviation.
- The transmission range is fixed or at least controllable.
- Each node can estimate its error characteristics.

Authors propose an algorithm called MER (Maximum Expectation within transmission Range) that mitigates the effect of noisy location information by explicitly considering the error probability when making routing decisions. To do so, error information field is attached to the message. In addition, the statistical characteristics of the location information are announced to neighbors with location errors. As for mobility, nodes try to predict their neighbors' locations. The routing decision requires knowledge about the furthest neighbor from the transmitting node, but also about the probability that its actual coordinates are within the transmission range (R). It then dismisses those forwarding options with either excessive distance or possibility of backward progress and is prone to choosing the node situated midway between the relays. Authors conclude that the degradation in the routing performance depends upon the transmission range of the sender, error characteristics of the sender and its neighbors, and the density of nodes. However, MER does not cope well with large errors (more than 32% of R) and the solution does not consider continuous moving nodes as their pause time is relatively large (up to 30s).

5.2.3.5 MER-Variants

a) CMSER and ECMSE

In [110], a conditioned mean square error ratio (CMSER) routing is proposed. The routing algorithm is intended to efficiently make use of existing network information and to successfully route packets when localization information is inaccurate. In CMSER, it is considered that the location errors are independent Gaussian random variables and that the error variance of each node is different while the probability density function of the distance between two neighbors follows a Rice distribution. Nodes' errors are statistically introduced. Next forwarder selection is based on the largest distance to destination (minimizing the number of forwarding hops) and on the smallest estimated error associated with the measured neighbor coordinates.

The energy constrained mean square error (ECMSE) [94] algorithm is an extension of CMSER. It is claimed that ECMSE minimizes the energy expenses of sensors while being robust to the localization errors. However, both protocols do not consider mobility of nodes in location estimation.

b) MER-EP: MER with minimum cost of error probability

The work in [111] takes into account the presence of uncertainties in the relays' locations and the communication channel fading, and a cost function is proposed to decide about the next hop relay. The factors to consider in defining appropriate metrics in the cost function are: (i) low probability of data loss; (ii) maximum rate of information arrival to the destination; and (iii) minimum impact of signaling and control on effective data rate. In order to achieve an efficient relay selection that takes into account all these factors, the channel capacity, together with the uncertainties statistics, are considered as a basis to derive formal expressions of two metrics. The first metric is the probability of error, defined as the relative amount of information lost when nodes have uncertainty in position and are subject to fading noise. The second is the progress of information in terms of the expected distance between hops toward the destination. This work is considered as an enhancement of MER [109] as the relay node is selected by choosing the node with the cost that minimized the error probability and maximizes the information progress. However, it does not consider the mobility of nodes nor sinks.

5.2.3.6. EEG

An Energy-Efficient Geographic Routing with Location Errors for WSNs has been proposed in [112] where nodes are supposed to be aware of their estimated positions and their location error bounds which can be potentially large (up to 100% of transmission range). The real position of a node x_i can be anywhere is the disk centered in the estimated position with a radius ε_i. According to this knowledge, it is possible to compute, before the deployment the probability that two sensors can communicate despite the localization error. EEG-Routing introduces a new metric which defines communication costs between neighbors, where each sensor forwards the packet according to the knowledge of the computing communication probabilities, energy consumptions and the progress towards the destination. Note that during data transfer, nodes also exchange the energy cost of the taken path. However, the proposed strategy was only for static networks.

5.2.3.7 GRPL

A Geographic Routing based on Predictive Locations is proposed in [204] for vehicular Ad hoc Networks (VANETs). In GRPL, each vehicle is aware of its location, speed and trajectory that are updated in a location server. Location and velocity information are measured by a GPS receiver. GRPL addresses the problem of time-lagged location information of the moving target vehicle by predicting its future location, knowing its previous location and its moving velocity. The prediction serves to reduce the request frequency of location updates (see Figure 22). Authors observed that the location error resulting from the prediction is proportional to the speed of the target vehicle and the update delay. In general, when the update delay is larger, the error is larger, and when the speed is higher, the error is larger. As for routing, once a new packet is injected into the VANET, the source node queries the location server for the current location information of the target vehicle, including its physical position, speed, and the corresponding timestamp. The source node appends this information to the packet header. Greedy forwarding is then used to choose the next forwarder node while priority strategies are used to choose which packets need to be forwarded first. The solution is delay-tolerant due to disconnections occurring in the network. Predicting the future location of the target vehicle helps in reducing the packet loss, however authors did not consider the location errors of neighbors. In addition, results show that the packet delivery ratio does not exceed 60% in all scenarios.

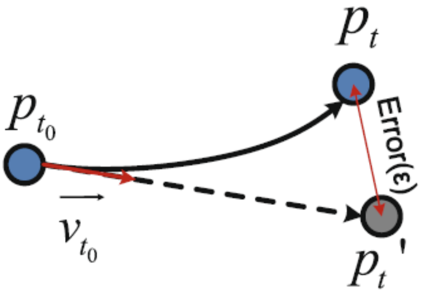


Figure 22: Location prediction in GRPL.

5.2.3.8. LER-GR

The very recent Location Error Resilient Geographical Routing (LER-GR) protocol was proposed in [101] for VANETs to cope with the inaccurate location information. In LER-GR, each vehicle determines its location and velocity by GPS. Rayleigh distribution-based error calculation technique is utilized for assessing error in the location of neighboring vehicles. Kalman filter-based location prediction and a correction technique are developed to predict the location of the neighboring vehicles while the next forwarding vehicle is selected based on the least error in location information. Figure 23 shows the estimation of future location of neighboring vehicles.

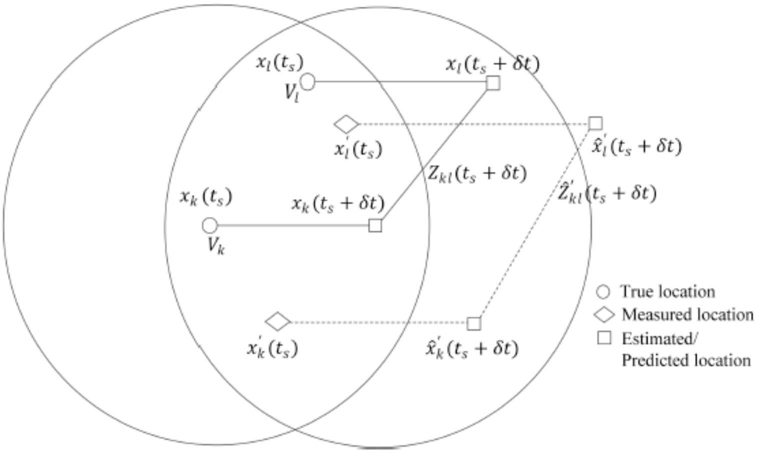


Figure 23: Prediction of neighbors' locations in LER-GR.

In LER-GR, the neighbor having the least location error is selected as the next forwarder. While this strategy increases trustworthiness between neighbors in forwarding data but cannot be sufficient alone, as the chosen forwarder may not be moving towards the destination or may be moving with a slow speed. Since the LER-GR was proposed for vehicular networks, energy was not a concern; In addition, this work did not evaluate the packet delivery ratio and the end-to-end delay of the proposed protocol, two metrics important for routing in

VANETs. Moreover, the maximum considered error represents only 20% of the transmission range while in VANETs, and with high speeds of vehicles, this error can be much larger.

6. DISCUSSION AND ANALYSIS

In this chapter, geographic routing has been studied in WSNs with a special attention to protocols for MWSNs and those considering localization error since two of the most significant factors affecting geographic routing protocols are nodal mobility and location accuracy. While the former also affects non-geographic routing protocols, the latter is a problem only when location is of use to the routing protocol.

The mobility can be divided itself into two main classes: mobility of sink (s) and mobility of sensors (whether with static sink or mobile sink). Most of research works considering mobile sinks focused their proposals on how to keep sensor nodes updated with the sink location either by querying the sink location from a central location server or by periodically flooding the network with a sink location query, or applying some prediction mechanisms to predict the sink location. Other works propose that the sink itself advertises its location either by periodically flooding the network with its new location or by locally informing the new neighbors, in the latter case, the sink location is propagated following the reverse path of data packets. Whereas research works considering mobile sensors focused their proposals on the neighborhood discovery and the next forwarder selection strategy. As for neighborhood discovery, most of reviewed works used proactive periodical 1-hop beaconing while next forwarder selection strategies differ from one protocol to another depending on which geographic criteria are used to make routing decisions. Some decisions were made based on the distances between nodes and destination, others considered the speed, or the direction, or both. While other works tried also to handle the local maximum problem.

Location inaccuracies are widespread in GPS and non-GPS (localization) systems and can have numerous undesirable effects such as nodes falsely entering the local maximum situation, routing loops, unreachable destinations being declared reachable, and the failure of face routing (location inaccuracy can cause network disconnection during planarization). Although GPS is generally considered the default location provider for most geographic routing protocols, some authors have acknowledged the possibility of using alternative systems (such as RSSI-based localization), and it is possible that most geographic routing protocols could function without GPS as long as another localization system would be able to provide them with coordinates. Although GPS does have limitations such as cost, energy consumption, inaccuracy, and has weak performance in indoor environments, it is important to recognize that alternative localization systems still represent an emerging area of research and cannot always guarantee better or even equal accuracy compared to GPS. Therefore, it is important to acknowledge the possibility of location errors regardless of the type of the system being used. One of the tools in achieving this is to determine the probability of a given node’s position being inaccurate, an approach used by MER [109] which uses the probability of location inaccuracy to determine the likelihood of a chosen node experiencing transmission failure or sending the packet backwards. Other variants of MER were then proposed for WSNs. Some works injected statistical location errors but were mainly proposed for static WSNs while those for MWSNs consider only GPS-induced errors. Table 1 summarizes the 21 reviewed geographic protocols for MWSNs upon selected metrics.

Table 1: Reviewed geographic routing protocols for MWSNs.

Geographic Protocol	**Destined Network**	**Mobile Nodes**	**Number of Sinks**	**Location Service**	**Error-conside-ration**	**Routing decision**	**Mobility Prediction**	**Beaconing strategy**	**Local Maximum handling**
Elastic	mWSNs	Sink	1	GPS, overhearing	No	Distance	No	Not specified	Not discussed
ALURP	mWSNs	Sink	1	GPS	No	Distance	Via Master Sink	Not specified	Not discussed
EERPM	mWSNs	Sink	1	unknown	No	Distance	Yes	Not specified	Not discussed
ILSR	mWSNs	Sink	1	GPS	No	Distance	Yes	Proactive Periodic	Not discussed
QoS Predictive pro	mWSNs	Sink	1 or multiple	unknown	No	Mobility Graph	Yes	Flooding	Not discussed
GPSR	MANETs	sensors	1	GPS	No	Distance	No	Proactive Periodic	Yes
GPSR-MS	MWSNs	sensors	1	GPS	No	Distance, speed	No	Proactive Periodic	Yes
MAGF	MWSNs/ DTNs	sensors	1	GPS	No	Distance, speed, direction	No	Not specified	Yes
PAGER-M	MWSNs	sensors	1	Not specified	No	Distance, shadowing	No	Proactive Randomized	Yes
M-GeoCast	MWSNs	Sinks and Sensors	multiple	GPS	No	Distance	No	Mobility depending	Not discussed
LASER	MWSNs	sensors	1	GPS	No	Blind	No	Proactive Periodic	Yes
AeroRP	ANs	Flying sensors	1	GPS	No	Distance, Speed, Direction	No	Proactive Periodic	Not discussed
TBGR	DTNs	sensors	1 or multiple	GPS	No	Distance, Speed, Direction	No	Not specified	Yes
MER	WSNs and MWSNs	sensors	1	GPS	Yes	Distance, Location Error	GPS-based	Proactive Periodic	Yes
CMSER and ECMSE	WSNs	No	1	Not specified	Yes	Distance, Location Error	No	Not specified	Not discussed
MER-EP	WSNs	No	1	GPS	Yes	Distance, Location Error	No	Proactive Periodic	Not discussed
ALBA-R	WSNs	No	1	GPS	Yes	Distance, Color	No	Proactive Periodic	Yes
ELLIPSE	WSNs	No	1	GPS	Yes	Ellipse Factor	GPS-based	Not specified	Not discussed
EEG	WSNs	No	1	Not specified	Yes	Location Error bound	No	Proactive Periodic	Not discussed
GRPL	VENETs	vehicles	multiple	GPS from central server	Yes	Distance	GPS-based	Not specified	Not discussed
LER-GR	VANETs	vehicles	multiple	GPS	Yes	Location Error	Statistical-based	Not specified	Not discussed

Thus, we can summarize the challenges of geographic routing for future considerations:

(a) GPS-free location information,
(b) Resilience to localization errors,
(c) Efficient forwarding mechanism,
(d) Bypassing local maximum/dead ends,
(e) Mobility induced challenges:
  - Efficient beaconing and location updates,
  - Link Loss avoidance,
  - Intermittent connectivity.

6.1 RESEARCH VACANCY AND CONTRIBUTIONS

1- Reviewed geographic routings protocols for mWSNs mainly tackle the location service of the mobile sink; and how sensor nodes get the update of the sink' new location. However, mobile sink location discovery is not the only issue with sink mobility. Other issues related to mobility of sinks may affect significantly the routing process such as the number of sinks, the presence/absence of the sink, the trajectory and speed of the sink.
  - ✓ In chapter 3, we propose a geographic routing that supports more characteristics related to sink mobility.

2- Most of geographic routing protocols for MWSNs consider GPS-enabled mobile nodes. Knowing that the network infrastructure setup with GPS is very expensive and energy draining, it would be better if new methodologies that provide cost effective and energy efficient location updates are explored further especially when dealing with random mobility patterns.
  - ✓ In chapter 4, we propose a GPS-free mobility prediction-based localization algorithm for mobile sensors with random mobility patterns.

3- Location awareness is fundamental for geographic routing. Most of proposed geographic protocols proposed in the literature assume that nodes can get their positions either by using GPS or other localization technique without mentioning which method was really used in case of non-GPS provided location. This makes interested reader or industrial confused whether the whole solution can be deployable in real world scenarios. We believe that since nodes locations are necessary to make routing decisions, any geographic routing proposal should make clear which localization method was used to obtain nodal positions.
  - ✓ In chapter 5, part of our proposal, we execute in parallel and jointly a localization algorithm with the proposed geographic routing. Thus making the used location service known to the reader.

4- In geographic routing for MWSNs, neighborhood discovery is a paramount. Most of proposed geographic protocols adopt a proactive periodic beaconing process neglecting its influence on the routing performance. However, in dynamic and mobile scenarios, this strategy consumes unnecessarily nodes' energy since discovered neighbors will change over time and neighborhood table will be quickly outdated.
  - ✓ In chapter 5, and part of our proposal, we use a reactive on-demand adaptive beaconing strategy where beaconing interval bounds are adapted to the mobility of nodes.

5- Earlier geographic routing schemes for MWSNs adopted blindly the greedy forwarding strategy that exploits the distance between nodes and sink. However, in mobile context, distance-only-based routing decisions are no longer sufficient.

   - ✓ In chapter 5, we propose a new relay selection strategy that considers nodal mobility patterns under realistic network models when making routing decisions.

6- Most of geographic routing protocols make the assumptions that nodes are aware of their exact locations. This assumption is unrealistic in real world deployment as location errors are inevitable. Some works consider localization error in routing decisions but most of them were proposed for static networks, while those proposed for mobile networks dealt only with GPS-induced errors.
   - ✓ Knowing that mobile nodes change their locations frequently so their location errors change over time, in chapter 5 and part of our proposal, we consider localization errors resulted from GPS-free mobility-prediction-based localization method in routing decisions.

7- Local maximum/dead end problem is one of the main concerns of geographic routing. Many proposed protocols tried to resolve this issue when it occurs by finding an alternative path and bypassing it using planarization or other similar strategies.
   - ✓ In chapter 5, part of our proposal, without the need for planarization, we take advantage of nodes' mobility to anticipate and reduce the occurrence of local maximum by considering nodes, which would be normally ignored in standard greedy forwarding, as valid candidates if they have the potential to make advance towards the sink.

8- Besides proposed protocols for VANETs, most of geographic protocols for MWSNs consider mobile nodes with a large pause time, which makes a mobile node, converge into a static node during this time, whilst the challenge for geographic routing comes from the lack of link reliability induced by high mobility especially during data transfer when nodes are continuously moving.
   - ✓ In chapter 5, we propose a geographic routing scheme that can be well applied in case of continuously moving nodes and even without pause time.

9- Mobility of nodes can cause intermittent connections in the network. Ignoring these potential disconnections may lead to performance degradation of the routing.
   - ✓ Our proposed geographic routing, detailed in chapter 5, can be well applied in intermittently connected networks.

CONCLUSION

The need to design efficient and scalable protocols makes geographic routing very attractive as it can be stateless, energy efficient and scalable especially for mobile networks known by frequent topology changes where geographic routing has fast response and can find new routes quickly by using only local topology information. The number of applications that can benefit from geographic routing is impressive. As a consequence, numerous routing protocols have been developed to better accomplish the routing process according to the application requirements. Reviewing the existing geographic routing protocols and selecting one for a specific application is not a very easy task due the large number of existing possibilities and the fact that each protocol tries to reach a trade-off between some network characteristics and application requirements.

In this chapter, we have surveyed more than twenty geographic protocols. To better match them with applications' needs, we have classified them into two main categories: *Protocols supporting mobility* where mobility of sinks and sensor nodes brings new challenges to routing in WSNs. The second category included protocols that consider *localization errors* in routing decisions since sensors cannot always get accurate positions. Non consideration of nodal mobility and location errors can affect considerably the geographic routing performance and may lead to transmission failures. We have also identified some research vacancies that will be considered in next chapters.

Contributions

Chapter 3: M-Elastic for Mobile Wireless Sensor Networks

Chapter 4: Localization for Mobile Wireless Sensor Networks

Chapter 5: INTEGER Geographic Routing for Mobile Wireless Sensor Networks

CHAPTER 3

M-ELASTIC supporting Sink Mobility Characteristics for Mobile Wireless Sensor Networks

INTRODUCTION

It is well known that in the case of a static sink the energy consumption of individual nodes varies strongly across the WSN, since the nodes close to the sink are much more heavily burdened than those farther away from the sink due to relaying operations [14]. As we have mentioned in chapter 1, many applications such as target tracking, emergency response and smart cities need the design of a routing protocol that considers mobile elements as part of the design. Some geographic routing protocols with mobile sinks [80-84] have been proposed in order to respond to certain specific applications as well as for improving the network performance. However, they mainly tackle the location service of the mobile sink; and how sensor nodes get the update of the sink's new location. Nevertheless, mobile sink location discovery is not the only issue with sink mobility. Other issues related to mobility of sinks may affect positively or negatively the routing process such as the number of sinks, the presence/absence of the sink, the trajectory and speed of the sink.

In this chapter, we study the sink mobility characteristics more in depth and we propose a geographic routing that supports more characteristics related to sink mobility and cope with its side effects. We call the new protocol M-Elastic for Modified-Elastic.

The chapter is organized as follows: Section 1 presents some direct related work. Section 2 highlights the main characteristics of sink mobility. A brief recall of Elastic routing is presented in section 3. Our improvement propositions are detailed in section 4. Simulation assumptions and results are discussed in section 5. Finally we conclude this chapter with a conclusion.

1. RELATED WORK

In chapter 2, we have reviewed some geographic routing with mobile sinks. Most of them focus on how to get location updates from the sink and how to optimize the network performance by maximizing data delivery, finding shorter paths or avoiding flooding, etc. Few works cared about sink mobility characteristics and their impact on the network performance.

In [113], authors evaluated the ability of data transmission and reception of WSN to a mobile sink on the basis of its speed; they conclude that the maximum data delivery depends upon this parameter. Stojmenovic et al. discussed in [114] the sink mobility in WSNs either in delay-tolerant networks or in real-time networks. They investigated the theoretical aspects of the uneven energy depletion phenomenon around static sinks and addressed the problem of energy-efficient data gathering by mobile sinks.

Authors in [73] highlighted the importance of multiple mobile sinks in WSNs and proposed a new geo-casting protocol that allows the dissemination to multiple mobile sinks, while in [115], authors observed through simulation the impact of a single mobile sink in WSN. They employed a mobile sink to a multi-hop routing platform namely the connected *K*-neighbors (CKN) sleep algorithm. The first scenario considers a mobile sink that moves randomly within a rectangular area and then another within a restricted circular area and finally, an event-driven sink. These scenarios were compared with the results obtained when considering a stationary sink. Authors concluded that sink mobility maximizes the network lifetime especially in the case of event-driven where the sink moves towards the source to get the packet.

Authors of [116] identified and highlighted the interactions between the controlled mobility and the layers of the control stack in self-organizing wireless networks and came up with a case study in which they show how controlled mobility can be exploited practically. Their advantages and limitations were also presented.

In the following section, we will discuss the sink mobility characteristics and their impact on the network.

2. MOBILE SINKS

The sink mobility assumption can be imposed by the application nature. For example, in security constrained scenario, if a static sink is located, it can be easily compromised and damaged by malicious users, causing disconnection between sensors and end-users [117]. Hence, the use of a mobile sink makes harder the damage of such component.

It is commonly agreed that a sink node is a powerful device with unconstrained supply energy and computing capacity. In addition, the following characteristics of the sink can critically influence the communication operations in sensor networks.

A) The number: even though the typical number of sinks is “one”, in most practical applications such as Emergency Response, the increase in the number of sinks provides more robust data collection and helps to increase the network lifetime and reduces the communication overhead within the network. In addition, it alleviates the uneven energy depletion problem of a single-sink deployment and can bring more uniform energy dissipation, therefore, the possibility of energy hole can be reduced and network coverage can be improved [5].

B) The mobility: during the lifetime of the network, the sink can be stationary or mobile. In some cases, the mobility is derived by the application. For example, sinks are integrated in mobile devices such as mobile phones carried by mobile users or attached to animals or vehicles equipped with radio devices. The mobile sink could provide the ability to closely monitor the objects that we want to guard in the WSN and to look at the events as smaller granularity than static sinks [25]. For delay tolerant applications, single mobile sink in fact equals virtually multiple static sinks at different positions [5]. To support the mobility of sink, it is essential to manage the relationship between the moving speed of the sink and the tolerable delay associated with data transmission.

A mobile sink can either move at fixed or variable speed and can be considered as slow (up to 1 m/s), moderate (1 to 20 m/s), or fast (greater than 20 m/s) [12].

As frequent updates of the position of the mobile sink can generate excessive energy consumption of sensors, routing strategies manipulating mobile sinks should provide effective means for monitoring sinks to keep all (or some) sensor nodes updated for further data reports.

C) The presence: the sink can be continuously or partially present during the lifetime of the network. In the latter case, the routing protocol must support the temporary absence of a sink. Instead of dropping messages during the absence of the sink, messages can be buffered in source nodes or other predefined locations (i.e a set of sensors near the sink) waiting to be delivered to the sink when it is available again.

D) The trajectory: when considering a mobile sink, the sink trajectory can be arbitrary or predefined by the network administrator in order to cover the whole network. For example, the sink can be mounted on a helicopter or on a fire truck monitoring a disaster area. In the case where the sink moves in an arbitrary manner, some sensor nodes may never be visited or the sink may go far from the events, hence, not all events will be reported; whilst, if the sensors can predict the mobile sink’s movement, the energy consumption would be greatly reduced and data packets handoff would be smoother [118].

3. GEOGRAPHIC ROUTING- CASE: ELASTIC

If the sink is mobile, its location information must be regularly updated to the source nodes [119]. Further, since a rate of communication overhead is created during the update location information of the Sink node, the power consumption increases. Therefore, it is necessary to find an efficient method to update the location information of the mobile sink. Among the routing protocols that consider the mobility of sink and the efficiency of location updates, we are interested in Elastic Protocol.

In Elastic [80], a source node uses the Greedy forwarding before transmitting data to a mobile sink, and the location information update of the mobile sink is transmitted to the source node in the opposite direction along the same path used for data transmission. Data are transmitted to the new location of the mobile sink when its location information is found in the way of the data transmission, i.e one the nodes in the route knows the current location of the sink.

The location service is executed in the order A-B-C, as shown in Figure 1 (a). However, when the Sink node approaches to node B, as shown in Figure 1 (b), the service is performed in the order Sink-B-C since B is a neighbor of the sink and can directly know the sink position. When the sink escapes the transmission limit of node A, as indicated in Figure 1 (c), the sink node transmits the location information to node A (its last hop forwarder) via Unicast. Then, node A backups information for the new location of Sink and expects the new package, it changes then the destination of the packet with the new position and sends the next packet to the sink via Greedy Forwarding. In Figure 1 (d-f), while node A is sending this packet to the sink, node B can overhear this transmission and derives the new position of the sink and finds another route via Greedy forwarding to send the next packet. This process is repeated for each packet until the source knows the new position of the sink.

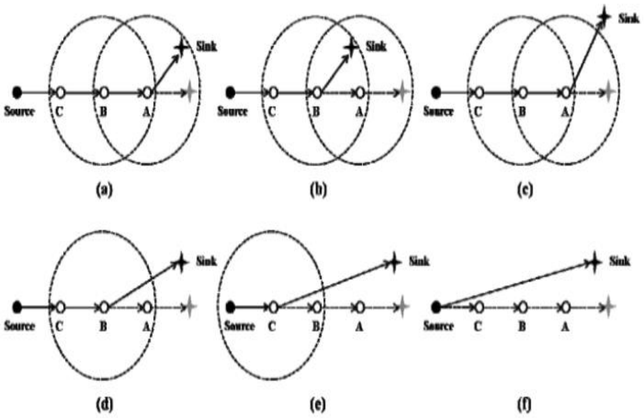


Figure 1: Location process in Elastic [80].

4. IMPROVING ELASTIC TO SUPPORT SINK MOBILITY CHARACTERISTICS

To support applications such as emergency response or smart cities where there is a great need to deploy multiple sinks, where each one has its own mobility model with different speeds and trajectories, we propose in this section, improvements and modifications to Elastic to support such sink mobility characteristics. Note that this work was published in |]

4.1 The Number

We suppose that multiple sinks are deployed. At the beginning the source node determines to whom the message is destined. This information is included in the packet with an additional list of the other sinks in the case where the first sink is not available. This list is considered as a reserve list. The order of this list is determined by the source node. If the last forwarder notices the absence of the main sink or fails to transmit the message to this sink, it checks the sinks' list and changes the packet destination with the first sink of the list. This strategy allows avoiding discarding messages in the case of sink's failure and even avoiding using face routing [75]. Indeed, if the last forwarder is faced to a local minima problem, and instead of using the planarization, it simply chooses another sink from the reserve list and then sends the message to this new destination (sink 2 in Figure 2).

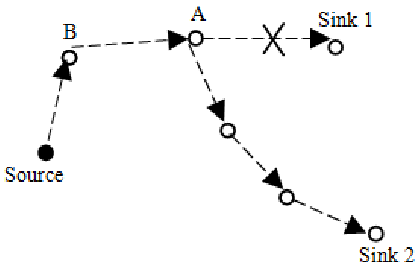


Figure 2: Managing multiple sinks in M-ELASTIC.

Algorithm 1 shows how the last hop forwarder chooses another sink from the reserve list whenever the main sink is not available.

Algorithm 1: Forward (i, pk, S, list)

```
// i is the packet holder,
// pk is the packet,
// list is the list of sinks, list={$S_1, S_2, \dots, S_n$}
1:  Begin
2:     $j \leftarrow 1$
3:     $S_j = list[j]$
4:     Forward (i, pk, Sj, list)
5:     if failure to find $S_j$ or local maximum then
6:         j ← $j + 1$
7:         Goto (3)
8:     Endif
9:  End
```

4.2 The mobility

The original Elastic routing was tested under few scenarios. In fact, authors have tested the protocol only when the sink follows a random way point model where the sink moves with a random speed between two bounds. Namely between 1m/s and 10m/s which are considered as slow speeds. Also, taking a random value in this interval may not be informative since the random value may be always close to the minimal bound. In order to get a clearer conclusion about how Elastic deals with sink' high speeds and when the sink is continuously moving, we propose to test it under a controlled mobility model and with more high speeds for the sink (See Section 5.2).

By the controlled mobility, we mean the sink knows in advance its moving speed and is constant during each network configuration, and the network administrator can control this speed. We allow the sink to move with high speeds in order to figure out the positive and negative effects on the network performance. Above 10m/s is relatively considered as high speed, simulating a UAV/UUV or a drone monitoring the sensed area.

4.3 The presence

During the lifetime of the network, and due to some circumstances, a sink can be temporary absent. For example, if the sink is mounted on a helicopter. When the helicopter goes far away from the sensor area, nodes cannot transmit their messages. An efficient routing protocol has to support such kind of situation. However, the original Elastic protocol does not address this problem at all. For that, we propose to improve Elastic routing so to support the temporary absence of the sink.

The deployment of multiple sinks can be of a huge benefit in the case of the absence of one sink (as proposed in Section 4.1), because there is a high probability to find another sink that can receive messages, even with longer routes.

The real problem occurs when there is only one sink deployed in the sensor area. In the following, we explain our proposition to improve Elastic so to support the sink absence.

Note that the last hop forwarder is the first who notices the sink absence.

- When the sink is absent, the last forwarder (node A in Fig. 3) buffers the received messages. If its buffer is full, it asks its neighbors (neighbors of A) to buffer the next received messages.
- If all the buffers of all the neighbors (neighbors of A) become full, the last forwarder delegates in turn its last forwarder (node B in Fig. 3) to receive and buffer the new coming messages. Remark: If the buffer of an intermediate node (a node belonging to the principal route) is empty, this means that the node still believes that the sink is available. In the contrary, if the node's buffer is not empty, the node concludes that the sink is not available and it is its task to ensure the buffering process.
- Then, in turn, the second last forwarder (node B in Fig. 3) executes the same process with its neighbors following the reverse path of the geographic routing during the data delivery, until arriving at the source node. From there, the source node understands that the sink is not available and all the buffers of the routing nodes are full and can no longer transmit new messages. We propose two solutions to face this problem at the level of the source node:
    - Not sending messages anymore until the sink becomes available again. But, what if there are more important messages than previous ones to be sent? The source node has to find another solution. We propose to prioritize messages. When an intermediate node receives a message with higher priority than the priority of the message it holds, it discards the old message and buffers the new one. Note that prioritized messages will replace old messages following the route to the sink. The order begins from the last hop forwarder following the reverse path of greedy forwarding.
    - Finding another route. However, if the sink absence period is very long, there is a high risk that the entire network faces a congestion problem because whenever a route is full, the source will look for another until exhausting all its neighbors. Since managing congestion is out of our scope, we omit this solution.

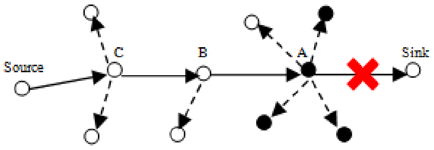


Figure 3: Buffering messages during the sink's absence.

Note that nodes buffer packets for a known period of time (buffering-time). If the buffering-time is elapsed and yet the sink is absent, nodes are then obliged to discard the packet to save their memory and energy. Flow chart in Figure 4 explains the algorithm managing the temporary absence of the sink by buffering messages in intermediate nodes.

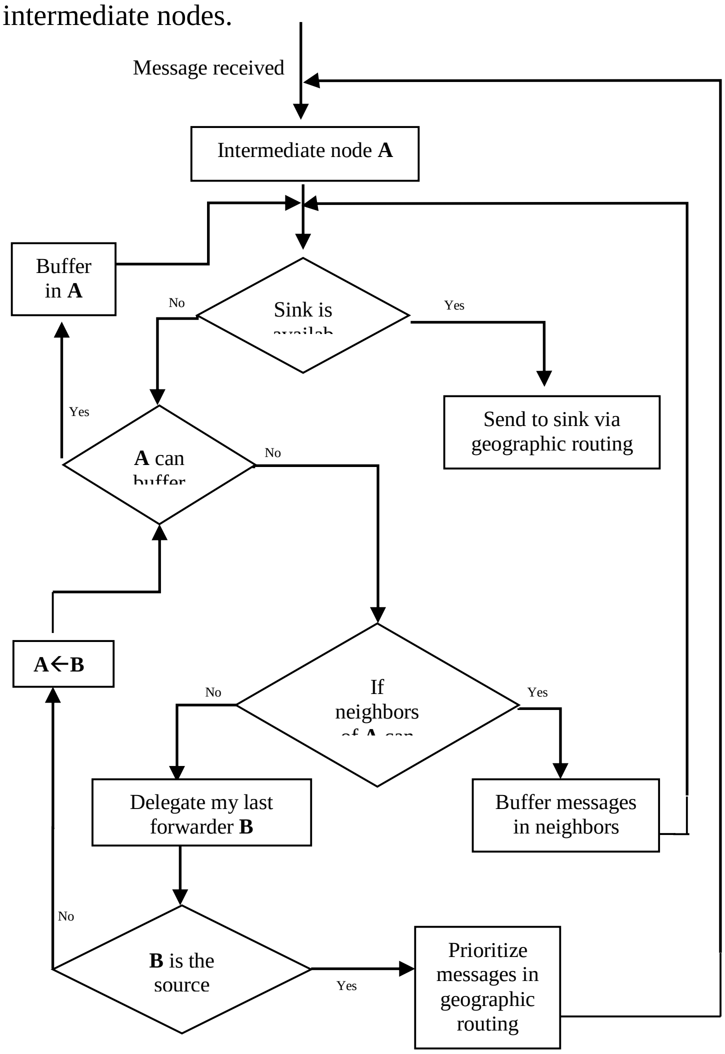


Figure 4: Flow chart for managing the sink's absence.

When the sink comes back, we use the same strategy as the sink location service, which is the overhearing concept. The sink informs by unicast its last hop forwarder (node A in Fig. 3) about its availability and its new location if it has changed. Node A begins to send its buffered messages to the sink. Neighbors of A overhear these transmissions (including node B) and notice the availability of the sink and its location. In turn, they transmit their buffered messages via greedy forwarding. Neighbors of B do the same thing and so forth until transmitting all the buffered messages and reaching the source node. From there onwards, the source is aware about the availability of the sink and can resume transmitting new messages normally.

4.4 The trajectory

In the original Elastic, before obtaining the new location of a mobile sink, the source still encapsulates the known original location of the sink in each data packet, and this invalid location information may lead to unsuccessful data delivery [80]. If the source can predict the new location of the sink, the delay of finding a shorter route can be highly reduced. However, authors did not mention whether the sink path is arbitrary or predefined, but in their tests, they supposed that the sink follows the random way point model, which leads us to deduce that the sink trajectory is arbitrary. This makes it hard to predict.

A) First Improvement

We suppose that the sink trajectory is predefined and the source knows the sink's trajectory and speed. This allows the source to predict easily the sink location at any time. Before sending a packet, the source encapsulates its belief about the sink location (the predicted location) on the data packet. This allows finding a shorter route to the sink's new location instead of sending the packet through the old path until arriving at a node that knows the new location of the sink. The predicted location by the source may not be the exact location of the sink but at least the packet will be sent in the right direction towards the sink and will meet surly one of the sink' neighbors since anyway the sink communicates its current location to its nearby sensors periodically. Despite this, we keep the overhearing principle so that the source node can update the sink real location since the location got by overhearing is more credible that the predicted one.

B) Second Improvement

In the original Elastic, with a higher moving speed, the sink may move out of the radio range of the last hop forwarding node with a higher probability. In this case, the sink has to inform its location to the last hop forwarding node by unicasting, and the data packets forwarded by the last hop forwarding node during this period are all dropped [80]. If the last hop forwarder can predict the new location of the sink, the number of dropped messages can be reduced. However, the last forwarder is not always the same, so we propose that all nodes know the sink's trajectory and speed. This allows nodes to predict easily the sink location at any time. While waiting the unicat message from the sink, the last forwarder encapsulates their belief about the sink's new location.

Now, the sink location extracted from overhearing messages is no longer the only information about the new location of the sink but it is considered as a trusted update helping as a basic reference for nodes to predict the sink location after a certain time.

5. PERFORMANCE EVALUATION

In this chapter, our goal is to observe the impact of sink mobility characteristics on Elastic geographic routing protocol and to improve it so to support these mobility characteristics. By simulating our improvement proposals using NS2 simulator [143], we analyze the performance results by means of calculating the delivery ratio of the transmitted packets, as well as the average delay of transmission and the number of hops necessary to transmit successfully a packet from the source to the sink.

We generate a sensor network with 100 nodes distributed uniformly in an area of 200 x 200 m^2 with a transmission range of 30 m. This gives a density of 7.07 following the formula (1):

$$\mathbf{D} = \frac{\pi N R^2}{A} \qquad (1)$$

Where ***N*** is the total number of nodes, ***A*** is the sensor area and ***R*** is the transmission range.

The sink (s) is (are) continuously moving without pause time, In Elastic routing, the sink sends location announcement messages once it moves 1 m away from its previous location. Each second, the source node (which is determined beforehand) sends 10 packets to the sinks (at the position that it holds about the sinks). Note that the simulation results are averaged over 10 runs. Table 1 summarizes the default simulation parameters. We suppose that all the nodes except sinks have fixed positions during all the simulation time and have the same energy of transmission and reception. Note that the rate packet loss is not due to collision but to the different scenarios of sink mobility.

Table 2: Simulation Parameters for M-ELASTIC.

Parameter	**Default value**
Number of nodes	100
Area size	200x200 m²
Mac layer	800.11
Communication range	30m
Antenna	Omni Antenna
Propagation	TwoRayGround
Packet size	512 bytes
Sink speed	20m/s
Sink trajectory	arbitrary
Simulation time	200s

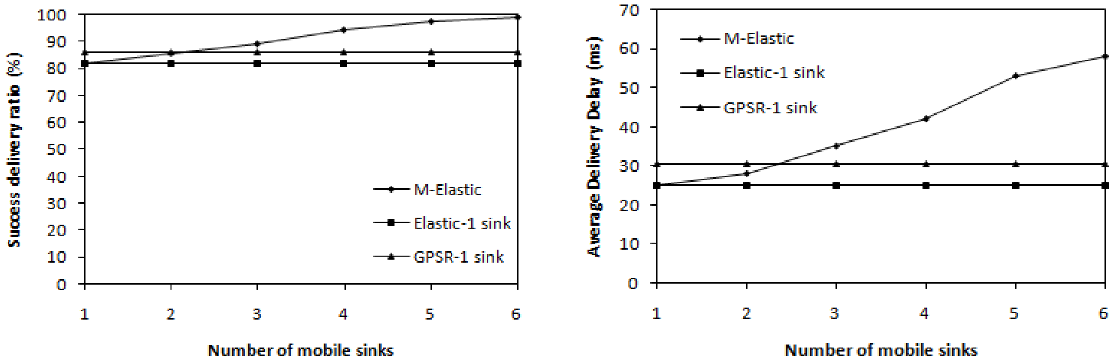
We compare M-Elastic with Elastic [80] and GPSR [75] as it is considered a reference for geographic routing in Ad Hoc networks and sensor networks.

5.1 M-Elastic considering Multiple Mobile sinks

To support multiple sinks, we have proposed that the source node determines to whom the packet is destined with a reserve list. In this test, we vary the number of mobile sinks and we study its effect on the delivery ratio and the average delay of transmission. After 50% of simulation time, we provoke intentionally the failure of the main sink and after 70% of simulation time; we provoke the failure of the first sink in the reserve list.

As shown in Figure 5 (a), with the increase of the number of the mobile sinks, the success delivery ratio increases too. Indeed, the more the number of sinks increases, the more a packet has the chance to be received by one of the sinks of the reserve list in case of delivery failure to some sinks.

Now, we measure the average delivery delay. We notice according to Figure 5 (b) that the delay increases when the number of sinks increases. This can be explained by two factors: first, the deployment strategy where in order to have a good coverage; sinks are deployed initially in relatively distant areas (otherwise, no significant advantage can be derived) while the source remains static. Then, they move arbitrary and may become more and more distant from the source. As a consequence, the number of hops increases and so the delay. The second factor is due to the failure of some sinks. This obliged the last hop forwarder to choose a sink from the reserve list and begin another route discovery towards this new sink which needs additional time. Note that the transmission delay is proportional to the number of hops. Indeed, whenever, the path length increases, the delivery delay increases too.

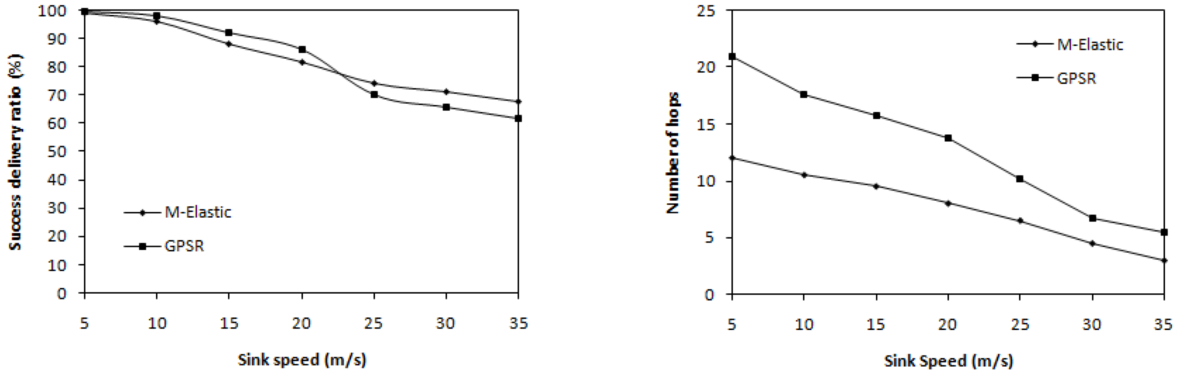


(a) (b)

Figure 5: (a) Delivery ratio with multiple mobile sinks; (b) Delivery delay with multiple mobile sinks.

5.2 M-Elastic considering Sink High Speeds

In the original paper of Elastic [80], authors tested their protocol under low speeds (maximum speed is from 1m/s to 10m/s) and the sink moves with a random speed between 1m/s and 10m/s. However, authors did not mention if there is a pause time or not. In addition, the real speed of the sink is not known. The scope of this chapter is to test Elastic under more different sink characteristics. To do so, we consider, in this test, one single mobile sink and we vary its speed between 5m/s and 35m/s. the sink's speed is known and constant during a test. The choice of this interval is motivated by the different applications that can benefit from mobile sinks. For example, in the case of an emergency situation, the sink can be mounted on a fire truck or even a civil helicopter (The speed can be higher than 20m/s). In smart cities, the sink can be attached to persons or vehicles (the speed can vary between 5m/s and 20m/s). Figure 6 (a) shows the success delivery ratio and Figure 6 (b) shows the average number of hops. For M-Elastic, with a higher moving speed, the sink may move quickly out of the radio range of the last hop forwarding node with a higher probability. In this case, the sink has to inform its location to the last hop forwarding node by unicast, and the data packets forwarded by the last hop forwarding node during this period are all dropped, this leads to degradation in the delivery ratio. In the other hand, when the sink speed is high, the sink may move towards source node quickly. This reduces the path length and so the number of hops while for GPSR, the number of hops is always above those of M-Elastic since GPSR does not rely on the overhearing concept, thus knowing the sink locations is harder especially with higher moving speed of the sink which explains the degradation of the delivery ratio.



(b)

Figure 6: (a) Delivery ratio vs sink speed; (b) Number of hops vs sink speed.

5.3 M-Elastic considering Sink Absence

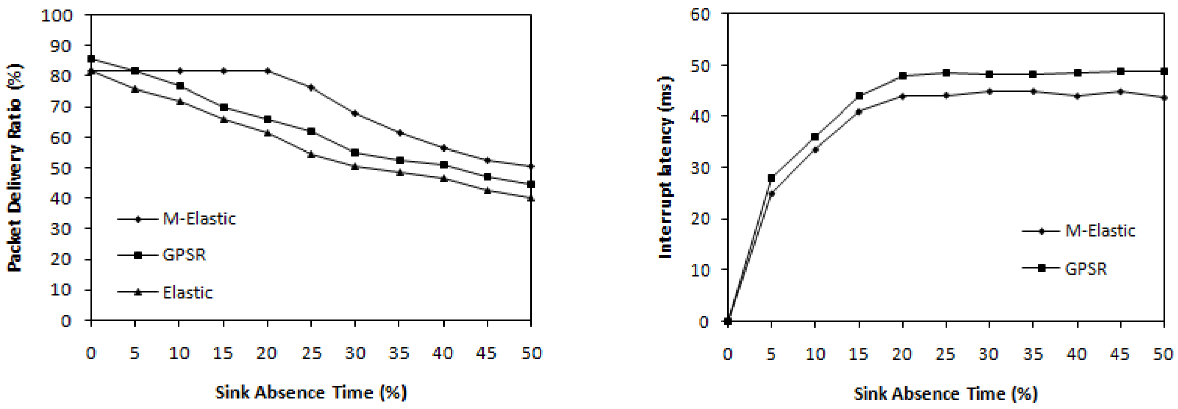
In this test, we vary the sink absence duration between 10% and 50% of the simulation time. We assume that each node can buffer up to 2 packets. The sink speed was set to 20m/s and the buffering-time was set to 5s. The packet generation rate was set to 10 packets /s. We suppose that during the absence of the sink, generated packets have more and more priority.

Figure 7 (a) shows the percentage of the packets delivered successfully with respect to packets transmitted during the absence of the sink. For M-Elastic, the results reveal that the delivery ratio remains constant until 20%. Indeed, during the absence of the sink, intermediate nodes buffer the packets, each one up to 2 packets in our case. If their buffers become full, packets will be buffered in their neighbors. When the sink is available again, nodes holding packets send them to the sink via geographic routing along the initial path. All packets reach the destination; packets were just blocked for moments. In our case, the density is 7, meaning that each intermediate node has around 7 neighbors. After 20% of absence, the route path becomes full (all intermediate nodes and their neighbors are buffering packets) because the average path length is 7-8 hops as deduced from Figure 6 (b), source node begins to prioritize packets and old packets will be dropped. In addition, after 25% of sink's absence, nodes begin to discard packets to save their energy and memory. All these factors explain the degradation of the delivery ratio but still there is a gain instead of dropping them all compared to the original Elastic and GPSR. Figure 7 (b) shows the average interrupt latency of a packet. That is, the transmission time from the comeback of the sink until arriving at destination. Obviously the end-to-end delay is calculated following this formula:

End-to-End Delay = Time for greedy forwarding + sink absence Time + Interrupt Latency (2)

Note that we applied the same buffering strategy to GPSR to compare it with M-Elastic.

From Figure 7 (b), we notice that the interrupt latency increases gradually until 20% of absence. This is explained by the fact that when the sink is back, buffered packets will be released in their order of arrival to be delivered to the sink. Thus, newest packets will wait the transmission of oldest ones. After 25% of sink absence, the route becomes full (intermediate nodes and their neighbors are all buffering packets) and prioritized packets will replace oldest ones. When the sink is back again, packets will be sent in the same order as before prioritization. Note that after prioritization, the number of buffered packets is the same since the route is full. What happened is only replacement of packets, this explained the almost stability in interrupt latency. We notice from Fig. 7 that the degradations follow Exponential Distribution for both M-Elastic and GPSR.



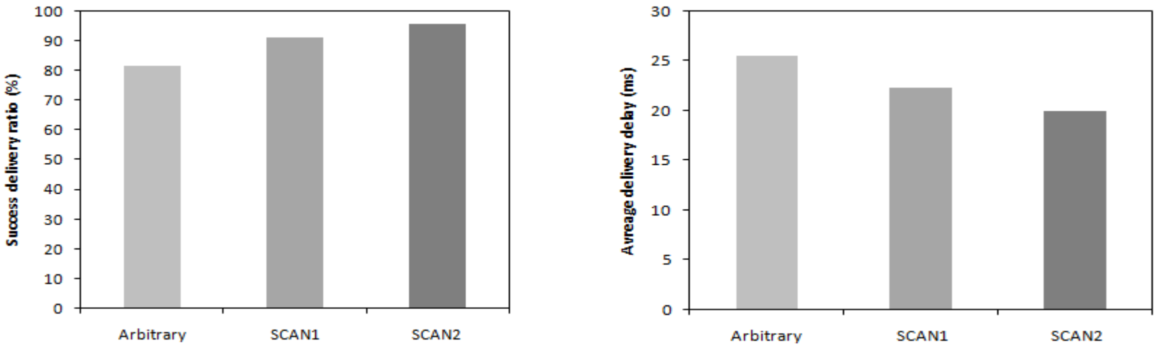
(a) (b)

Figure 7: (a) Impact of the sink absence time on delivery ratio; (b) Delivery delay vs sink absence time.

5.4 M-Elastic considering Sink Trajectory

In the last test, we evaluate the M-Elastic protocol with first, an arbitrary trajectory of the mobile sink without any prediction and then with a predefined trajectory namely SCAN [120], SCAN1 means that we have used our first improvement, that is only the source node that knows the sink trajectory and can predict its location. SCAN2 means that we have used our second improvement, that it, all nodes know the sink trajectory, thus can predict its location. We fixed the sink velocity to 20m/s. Figure 8 shows the impact of our strategy on the success delivery ratio and the delivery delay.

Clearly, Figure 8 shows that a mobile sink following a predefined trajectory gives better results in terms of packet delivery and average delay compared to an arbitrary one. In fact, with a predefined trajectory, source node can predict the new location of the sink and encapsulates this information on the packet. This allows finding quickly a shorter route to the sink's new location. With the second improvement, all nodes can predict the sink location, and while waiting the sink unicast, packets will not be dropped but sent to the predicted location. This will reduce the number of dropped packets as well as reducing finding another route, thus reducing the transmission delay.



(a) (b)

Figure 8: (a) Impact of the sink trajectory with location prediction on delivery ratio; (b) on delivery delay.

CONCLUSION

In this chapter, we have proposed improvements to the geographic routing protocol Elastic to support different sink mobility characteristics namely the multiplicity of mobile sinks, the temporary absence of the sink and higher speeds of the mobile sink. The results reveal that with multiple mobile sinks and thanks to our strategy of reserve list, M- Elastic gives better results in terms of success delivery ratio. However, whenever the sink' speed is high, the delivery ratio becomes lower but with the advantage of having less number of hops, that means less delivery delay. Thus in real-time applications we suggest to deploy a mobile sink with high speed. The major improvement we have done is modifying Elastic so to support the absence of the sink. Instead of dropping packets during the absence time and thanks to our strategy of buffering and prioritizing packets, M-Elastic saves up to 25% of packets sent from being dropped and important packets will be sent even after the fullness of the route. Finally, predicting the sink location improves the delivery ratio and reduces the delivery delay.

CHAPTER 4

Prediction-based Localization for Mobile Wireless Sensor Networks

INTRODUCTION

Geographic routing in mobile sensor networks requires the knowledge of nodes' locations. However, localizing mobile sensors is a very challenging problem that did not receive enough research. Still, there are no standards and most geographic routing protocols assume GPS-enabled mobile nodes. One of the recent proposed methods for MWSNs is SDPL [121] (Speed and Direction Prediction-based Localization) that estimates the sensor position with the prediction of its real speed and direction that the sensor moves with. SDPL assumes that a mobile anchor moves in the sensor field and sends periodically position beacons to help localizing mobile nodes.

In this chapter, we propose two extension methods of SDPL. The first is MA-SDPL that considers multiple mobile anchors. The goal is to heighten the number of beacons that a node receives, and to increase the quality of received beacons to get more accurate estimations. The second is called MH-SDPL that works with the multi-hoping fashion. In MH-SDPL, when a node is well localized, it participates in the beaconing process. We conduct a series of tests and compare the results with the basic SDPL.

The chapter is organized as follows. Section 1 briefly presents some direct related work. Section 3 reviews the basic SDPL method. Section 4 and 5 present in details the two proposed methods MA-SDPL and MH-SDPL. In section 6, simulation results are presented and discussed. We finish this chapter with a conclusion.

1. RELATED WORK

Locating mobile sensors is a very challenging problem [122] since sensors change frequently their positions and often with no information about their next destinations. Many GPS-less localization methods have been proposed in the literature to localize mobile sensors. Among the most promising methods, we find the probabilistic ones.

Authors is [123] propose the use of the probabilistic Monte Carlo method to predict of the next position using received anchor beacons and the maximum speed of the mobile nodes. The method does not consider any information about the direction of the nodes and assumes that all the nodes move with the same speed.

The method proposed in [124] uses a mobile robot to predict the position of nodes in an indoor environment. The method is based on a Probabilistic Graphical Model (PGM) that estimates the sensor node position using range-only measurements of the received signal strength indicator (RSSI). Even if the method was validated by real-world experiments attesting that the probabilistic model is suitable, but the method do not consider the mobility of nodes. More surveyed localization methods can be found in [64].

Authors in [121] propose a method called Speed and Direction Prediction-based Localization to predict the speed and the direction of the mobile nodes to increase the accuracy of the localization estimations. Since our work is an enhancement of SDPL, in the next section we detail this method.

2. SDPL (SPEED AND DIRECTION PREDICTION BASED LOCALIZATION)

SDPL [121] is a distributed probabilistic method based on the prediction of the real velocities and directions a node moves with. This allows unknown mobile nodes to better localize themselves. In addition, a single mobile anchor travels in the field and periodically sends messages that contain its current location (see Figure 1). Only the anchor can obtain its exact coordinates at any time (e.g. equipped with GPS) or in the case of a predefined trajectory, it can get its current position knowing its velocity and its trajectory. SDPL is mainly based on the prediction of the velocity and the direction of unknown nodes. To do so, SDPL authors supposed that nodes follow a rectilinear movement during small intervals (see Figure 2) where nodes have a constant velocity and direction during certain time periods (Δt). This reflects the reality where nodes (e.g. Human beings, cars, etc) keep their speed and direction, at least, for moments. This allows nodes to predict positions at time $T = T_0 + \Delta T$ with the following equations:

$$P_u(T) = \overrightarrow{V_u} \times \Delta T + P_u(T_0) \rightarrow \begin{cases} x_u = V_u \times cos\theta \times \Delta T + x_u(T_0) \\ y_u = V_u \times sin\theta \times \Delta T + y_u(T_0) \end{cases} \tag{1}$$

Where $\theta$is the angle between the abscissa axe and the speed vector $\vec{V}$. The speed is calculated as follows:

$$V_u = \frac{\sqrt{\left(x_u\,(T_0) - x_u\,(T_s)\right)^2 + \left(y_u\,(T_0) - y_u\,(T_s)\right)^2}}{T_s - T_0} \tag{2}$$

Where T_0 and T_S are times corresponding to two positions already estimated. If the calculated speed is equal to zero, the node deduces that it is static during Δ.

The angle θ defines the node direction.$\theta$is calculated as follows: $\tan\theta = \frac{y_u(T_0) - y_u(T_s)}{x_u(T_0) - x_u(T_s)}$ (3)

In case where a node has already estimated many positions and cannot receive anchor messages, it calculates the speed of each couple of its previous positions and takes the mean as its next speed prediction. In addition, to predict the direction angle, the node makes a linear regression with these positions to deduce, then, the line that provides a best fit for the data points using the *least squares* approach (See Figure 3).

After the prediction of the speed and the direction, a node estimates its coordinates (x,y) as follows:

$$\begin{cases} x = x_{prev} + \cos\theta \times speed \times T_{dif} \\ \end{cases} \tag{4}$$

$$y = y_{prev} + \sin\theta \times speed \times T_{dif}$$

Where (x_{prev}, y_{prev}) is the last estimated position; $(speed, \theta)$ are respectively the predicted speed and direction angle; $\boldsymbol{T_{dif}}$ is the time between current time and time of the last estimation.

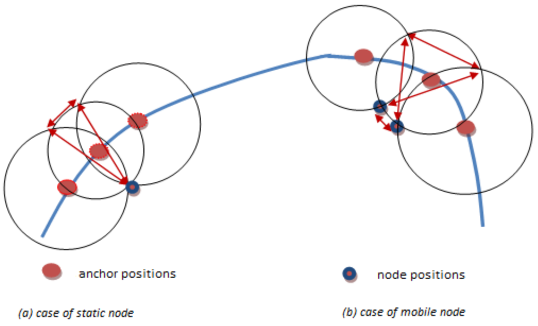


Figure 1: Estimation with three anchor messages.

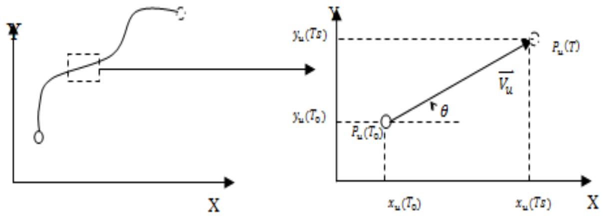


Figure 2: Speed and Direction Prediction in SDPL.

The idea of predicting the velocities and directions of the moving sensors is very promising and allows reducing the localization error [121]. But, one of the major drawbacks of SDPL is that at the beginning, the localization process relies on one single mobile anchor. That means that if the anchor stops to move for some reason or fails to cover the sensor area, the localization process fails and many sensors cannot localize themselves. To increase the chance of localizing sensors, we propose an extension of SDPL that works with multiple mobile anchors called MA-SDPL [131].

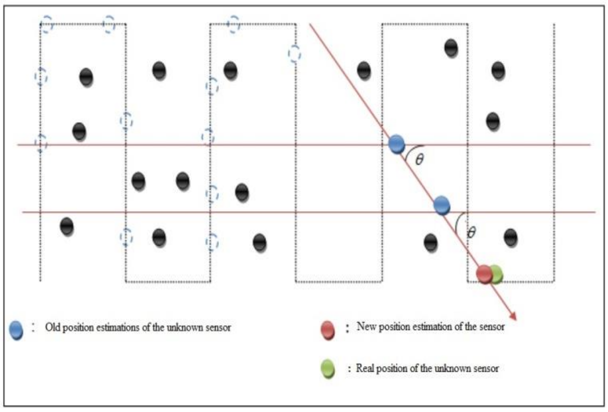


Figure 3: Location estimation with SDPL.

3. MA-SDPL (MULTIPLE ANCHORS- SDPL)

In an application such as Emergency Response, many fire trucks and ambulances circulate in the hit area to help evacuating victims. Anchors can be placed in emergency vehicles. From such scenario, the idea of using multiple anchors is come from. That is, embedding anchors on emergency vehicles. MA-SDPL relies on multiple mobile anchors to ensure the coverage of the sensor area and to increase the number of beacons a mobile sensor receives. Each mobile anchor has its own trajectory and velocity. When an anchor moves, it sends periodically beacon messages that contains its ID and its current location defined by the (x, y) coordinates (See Figure 4).

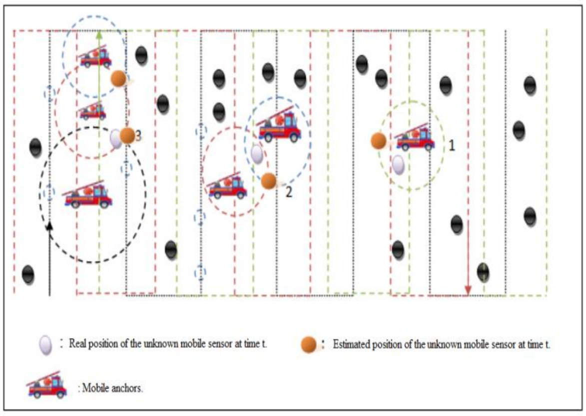


Figure 4: Emergency vehicles as mobile anchors.

The localization technique is the same as the basic SDPL. The difference lies in the number of beacons a node receives in an interval of time. The more the number of anchors is the more the number of beacons an unknown node receives. Thus, the occurrence of the case of velocity and direction prediction (that is when the unknown node receives more than three anchor messages) will be very high. Hence, the node estimates better its position.

In an application such as Emergency Response or Military Battle, the environment is very noisy and anchor messages may not be received properly by the other sensors. Figure 5 presents an example where some anchor neighbors are deprived from receiving location messages because of the noise. As a consequence, they cannot localize themselves accurately.

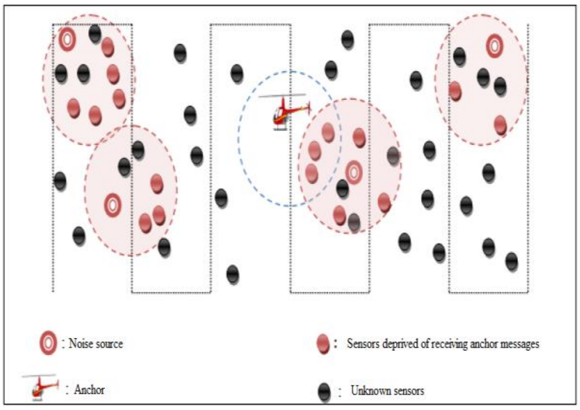


Figure 5: Noisy Environment Effect.

In Section 5.4, we will present in numbers the effect of noise on the localization error of MA-SDPL.

The idea of using multiple anchors to ensure the total coverage of the sensor area is good but not always realistic. The trajectory and the velocity is a key condition. Some sensors still cannot get anchor messages if the different anchors do not travel around them. In addition, not all applications need to use several anchors. Also, it may be costly since each anchor should be without energy constraints and may use GPS system. To overcome this condition, we propose a new extension of SDPL called Multi Hop SDPL.

4. MH-SDPL (MULTI HOP- SDPL)

MH-SDPL [145] is based on the multi-hop localization that is when a sensor has a good enough estimation of its position; it plays the role of an anchor. In other words, it sends its estimated position to its neighbors to help them localize themselves. The goal of MH-SDPL is to minimize the cost of using multiple anchors. For example, in a disaster management application, the main anchor can be a rescue helicopter that sends position messages to the responders in the hit area (see Figure 6).

Sensors placed in fire trucks or in ambulances receive these beacons and localize themselves and in turn they send their location estimations to the sensors attached to the rescuers in their vicinity. We call such localization, 2-hop localization and so on. The following figure shows an example of 2-hop localization in the case of an emergency application.

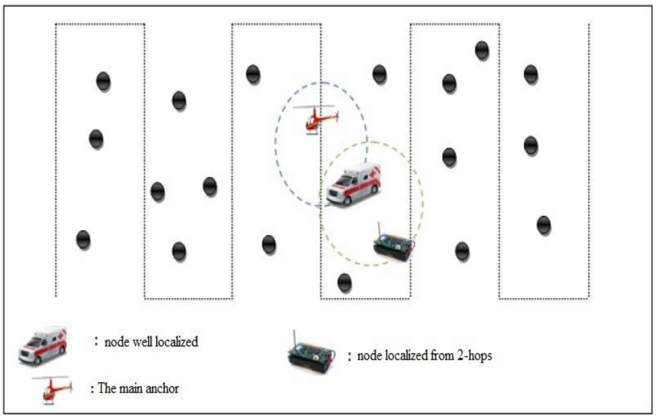


Figure 6: Example of 2- hop localization.

5. PERFORMANCE EVALUATION

To evaluate the two extensions of SDPL, we opted for simulation. Our simulations are performed using the Network Simulator (NS) [143] version ns-allinone-2.34. NS2 is widely used in academic network researches. To analyze the simulation results, the main metric is the localization error. The localization error is calculated as the Euclidian distance between the actual and the estimated position of a node. We consider the average localization error over all sensors.

We have chosen SCAN as a trajectory for the mobile anchors. For nodes mobility, we use the random waypoint mobility model [125] where each node can vary its speed and direction at each own time step. Table 1 summarizes the simulation parameters used in our tests.

Table 3: Simulation Parameters for Localization.

Parameter	Default value
Number of nodes	100
Area size	200x200 m^2

Mac layer	800.11
Communication range	30m
Antenna	Omni Antenna
Propagation	TwoRayGround
Mobility Model	RandomWayPoint
Anchor speed	20m/s
Anchor trajectory	SCAN
Sensors Maximum Speed	4 m/s

5.1 MA-SDPL: Impact of Number of Anchors

In the following test, we study the impact of the number of the anchors on the localization error using MA-SDPL. In this test, mobile anchors follow the SCAN trajectory and have different start points. The travelling time was set to 100s.

As we can notice from Figure 7, with the increase of the number of mobile anchors, the localization error decreases. In fact, the more the number of mobile anchors is, the more unknown nodes receive position messages from these anchors and the case of speed and direction prediction will be more frequent; hence nodes improve their location estimations. This explains the decrease of the mean error.

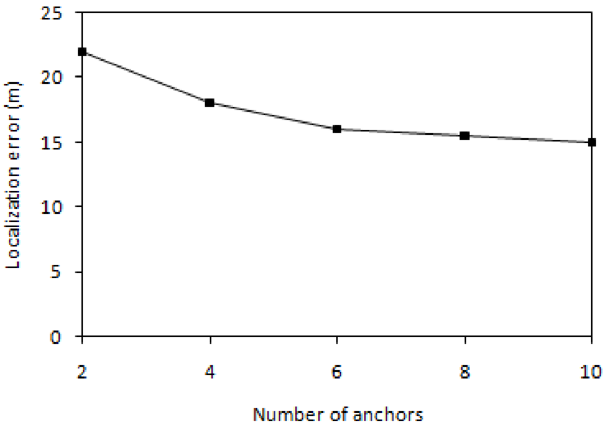


Figure 7: Localization Error vs Number of Anchors.

5.2 MA-SDPL: Impact of Travel Rounds

Travelling many times the sensor area has its impact on the localization error. When a mobile anchor travels many times the zone, unknown nodes receive more position beacons. Figure 8 shows the results obtained by deploying four mobile anchors that travel the sensor area more than one round. Note that increasing the number of rounds is similar to increasing the travelling time.

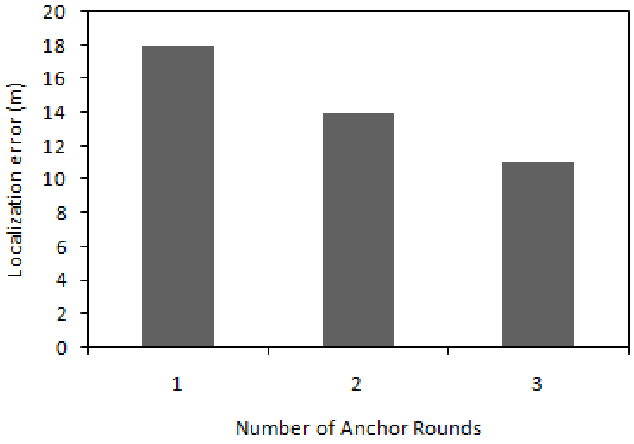
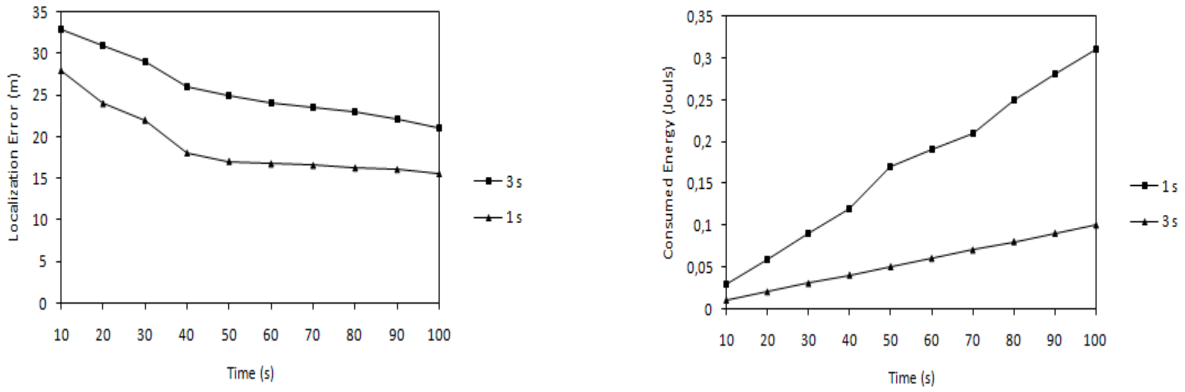


Figure 8: Localization Error vs Anchor travel rounds.

Initially, nodes have no knowledge about their positions. From the first round, nodes begin to estimate their positions hence the first round is a transition from the random positioning to a more accurate positioning. Obviously, when anchors travel the sensor area many times, unknown nodes receive more position messages from these anchors. And the more a node receives anchor messages, the more it uses the prediction of the speed and the direction which allows improving its location estimation.

5.3 MA-SDPL: Impact of Diffusion Interval

Another important factor is the anchor diffusion interval. The smaller the interval is, the more the number of anchor beacons a node receives. This effects directly its location estimations. Figure 9 (a) shows that when this interval is small, the location error decreases because unknown nodes get more information related to their mobility from the anchors and when nodes cannot receive any anchor messages, they use easily the prediction case. This improves their location accuracy.



(a) **(b)**

Fiigure 9: (a) Localization error vs Diffusion Interval; (b) Consumed Energy vs Diffusion Interval.

However, receiving much anchor messages consumes sensor energy. Figure 9 (b) shows the impact of the diffusion interval on the total energy. When the diffusion interval is small, the anchors send many messages during the localization time. This means that unknown sensors receive also many messages which deplete their energy.

5.4 MA-SDPL : The impact of a Noisy Environment

We have tested MA-SDPL under a noisy environment and called it MA-SDPL-N. 30% of noise means that 30% of the nodes inside a noisy zone cannot receive any anchor beacons or receive them with erroneous information. Note that the test was conducted with 4 mobile anchors following SCAN trajectory.

The noise has its side effect on the localization process (see Figure 10). In fact, in a noisy environment, location beacons may not be received by unknown nodes or the messages may contain wrong information. In one side, the nodes inside a noisy area cannot receive anchor messages and are obliged to draw random samples from the zone which increases the uncertainty leading to a high localization error. In the other side, those who are in less noisy zone receive some anchor messages but not sufficiently, hence they use more frequently the prediction case successively without refining their estimations with anchor messages. This increases the average location error.

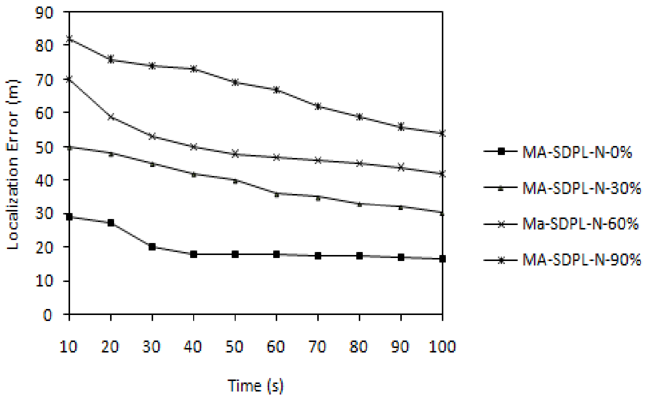


Figure 10: MA-SDPL-N.

5.5 MA-SDPL VS MH-SDPL

In the first test, we compare the average consumed energy between the two methods MA-SDPL and MH-SDPL. For MH-SDPL, only one mobile anchor is used unlike MA-SDPL where four mobile anchors were deployed. For both methods, mobile anchors follow SCAN trajectory. Note that in this test, MH-SDPL is 2-hop localization.

We notice from Figure 11 that for both methods the consumed energy is proportional to the execution time. Indeed, over time, nodes with MA-SDPL receive more anchor messages which consumes their energy. In the case of MH-SDPL, more nodes consider themselves as well localized and send their locations to their neighbors. As a consequence, their energy consumption of sending increases as well as the neighbors’ energy consumption of receiving.

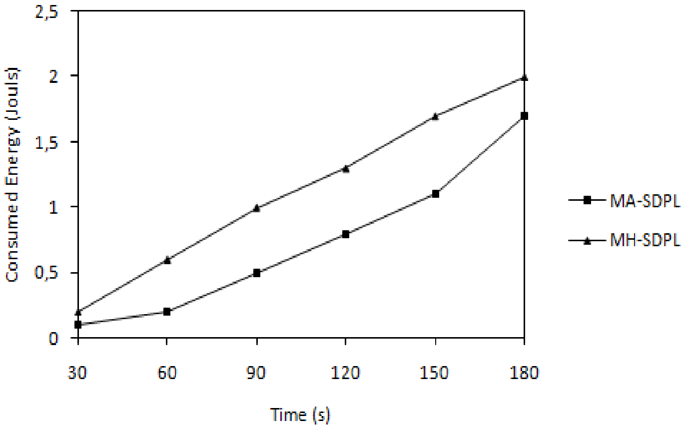
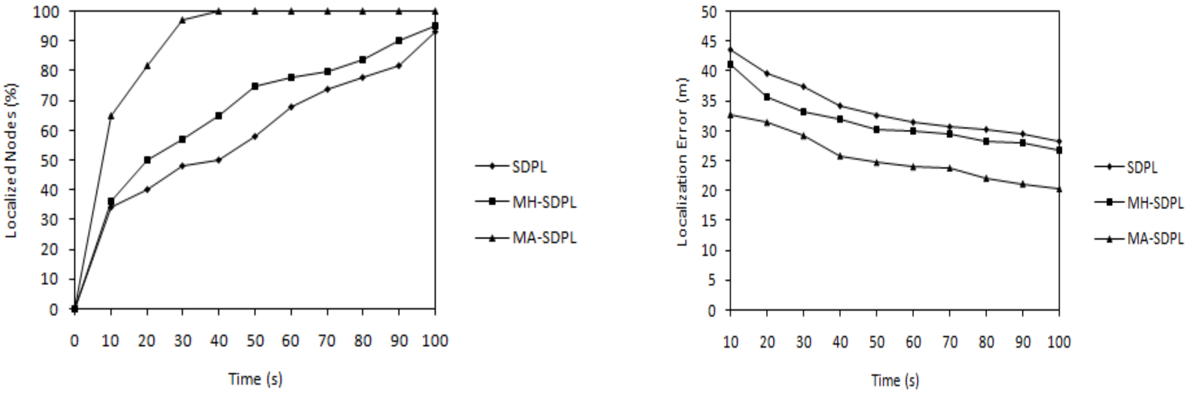


Figure 11: MA-SDPL VS MH-SDPL.

5.6 SDPL, MA-SDPL and MH-SDPL

In this section, we compare the three methods, the basic SDPL, MA-SDPL and MH-SDPL in terms of the number of localized nodes and the average error. Four mobile anchors were used for MA-SDPL while for the others only one was used. MH-SDPL is of 2-hops.



(a) (b)

Figure 12: (a) Localized nodes: SDPL vs MA-SDPL vs MH-SDPL; (b) Localization Error: SDPL vs MA-SDPL vs MH-SDPL.

Thanks to the multiple mobile anchors used in MA-SDPL and the fact that each anchor begins with its own starting point (in our case the four corners of the square area), unknown sensors have more chance to receive anchor messages hence to localize themselves even before that anchors travel the whole area. This explains the total coverage after just 40 seconds from the beginning of localization process (see Figure 12 (a)). In MH-SDPL, even with only one mobile anchor, the fact that well localized sensors participate in turn in the localization process by sending their location estimations to their neighbors, this help those nodes that cannot receive anchor messages to be localized or even enhance their location estimations. So the number of the localized nodes will increase.

Figure 12 (b) shows that by the end, MA-SDPL with four anchors gives results about 26% better than MH-SDPL with 2-hop localization and 31% better than the basic SDPL.

CONCLUSION

Our goal, in this chapter, was to propose a GPS-less localization method to localize mobile sensors to be used in geographic routing in MWSNs. The proposed methods can be considered as improvements of the method SDPL (Speed and Direction Prediction-based Localization) in terms of coverage, consumed energy and localization error. To do so, we have proposed to use multiple mobile anchors instead of one to cover the whole area rapidly and to help localizing the unknown sensors by giving them the chance of receiving location messages from more than one mobile anchor. From the simulation results, this new extension of SDPL called MA-SDPL has proven to be efficient. Indeed, the localization error was reduced considerably. In addition, the more the number of mobile anchors is, the less the localization error is. We have also tested MA-SDPL under a noisy environment. Obviously, when the noise is high, the average localization error is high too. In the case where multiple anchors are not available, we have proposed that some sensors play their roles. This is when a sensor is well enough localized; it plays the role of an additional anchor and sends in turn its location to its neighborhood while keeping its own mobility. The latter extension was called Multi-hop-SDPL. Overall, the results are promising and these methods can be a preliminary phase for geographic routing in MWSNs.

CHAPTER 5

Intertwined Localization and Error-Resilient Geographic Routing for Mobile Wireless Sensor Networks

INTRODUCTION

To date, there have been extensive studies on localization methods and on geographic routing algorithms for wireless sensor networks (WSNs), albeit mostly not covering both topics at the same time. Proposed geographic routing protocols often assume that nodes' positions are known either using Global Positioning System (GPS) or other localization methods and neglecting the possible localization errors of these approaches. A number of localization methods were proposed for mobile sensor networks [64, 126-130]. Yet, all these localization methods give only estimations and errors are inevitable. Without considering these location errors in geographic routing, routing decisions can be totally erroneous thus leading to a high rate of packet loss. In addition, the mobility of nodes can cause intermittent connectivity that affects significantly the communication characteristics in the network [71]. Therefore, novel communication and routing techniques dealing with this lack of reliability are required.

In this chapter, we propose a new approach to the problem of routing in mobile networks in the presence of location errors. Specifically, we propose an INTertwined localization and Error-resilient GEogranphic Routing (INTEGER) protocol [146], which combines mobility-prediction based localization, on-demand neighborhood discovery, relay weighted-selection and delay-tolerant geographic routing. The protocol is composed of two intertwined algorithms. Speed and Direction Prediction-based Localization (SDPL) for localizing mobile nodes which is an improvement of our works published in [121] that gives an estimate of the location error bound to be considered in the routing phase. The other algorithm is a new geographic routing that uses on-demand neighborhood discovery and exploits the results of the improved localization algorithm to route packets considering the location-error, the mobility of nodes and the intermittence of the connections. To the best of authors' knowledge, INTEGER is the first method to include a joint prediction-based localization and geographic routing while considering the location error and the mobility of all nodes. Extensive ns2-based simulation experiments are performed to demonstrate how INTEGER deals with location errors of mobile nodes. We have compared the performance of INTEGER to that of six routing protocols from the literature under different network scenarios and parameter settings. The results show that when varying the speed of nodes INTEGER improves the energy efficiency by 33%, increases the packet delivery ratio by 24% and reduces the number of relay nodes by 42% while maintaining a reduced delivery delay.

This chapter is organized as follows: Section 1 gives some motivations about our proposal. INTEGER is described in details in Section 2.1 (Localization method) and Section 2.2 (Routing algorithm). Section 3 shows the performance evaluation of INTEGER under different network scenarios and a demonstration of the effectiveness of INTEGER in efficiently handling the localization errors under high mobility of nodes. Possible adaptation of INTEGER in Delay-tolerant networks is studied in Section 4. Finally, a conclusion is provided at the end of this chapter.

1. MOTIVATIONS

Most of reviewed geographic routing schemes assume that the mobility patterns and the exact positions of the mobile nodes are known and those which consider localization errors deal only with static nodes or only assume mobile sinks. Besides, those which consider the mobility prediction and location error assume nodes are equipped with GPS to get their exact velocity at any time. No previously published work proposed a geographic routing for mobile sensor networks executed together with mobility prediction-based localization when all nodes are mobile. The novelty of our proposal is that it gathers many realistic characteristics of WSNs in one, namely:

- Being both geographic and GPS-free
- All nodes can be continuously mobile
- Using a localization method based on mobility-prediction
- On-Demand and Mobility-based Adaptive neighborhood discovery
- Considering jointly the distance, location-errors, mobility patterns of nodes and the reliability of links in routing decisions
- Can be also suitable for intermittently connected networks and Delay-tolerant networks.

In light of the previous review in chapter 2 about the effect of the direction and the speed of mobile nodes in addition to the localization error on next forwarder selection, and to overcome their related consequences, we present in the following section our intertwined localization and routing scheme.

2. INTEGER: INTERTWINED LOCALIZATION AND ROUTING METHOD

In this section, we propose a novel intertwined localization and routing scheme, namely INTEGER, for mobile sensor networks. We assume that sensor nodes have the same communication range and can devise neighbor distances based on the received signal strengths from their neighbors. The position of the destination node (i.e., sink) is known to all sensor nodes. In case of mobile sink, we assume that it follows a predefined trajectory so that sensor nodes can know its current location at any time, thus relays can update the destination location of the packet before making routing decisions.

We propose a fully distributed localization and routing protocol. The protocol is composed of two intertwined algorithms; one for localization mobile nodes with an assisting mobile anchor, and then a geographic routing that uses results of the localization algorithm. At the beginning, an initialization phase of nodes' localization is necessary to serve as a preliminary step for the routing protocol. After relatively a stable time (generally after that the mobile anchor finish traveling letting nodes predicting their positions without the anchor assistance), the source nodes (randomly chosen and deployed) begin to send packets to the sink; and then the two algorithms continue simultaneously their execution. Note that mobile nodes estimate their positions periodically to be ready to communicate their location information when needed as detailed in the following sections.

2.1 LOCALIZATION ALGORITHM

In this section, we describe our proposed localization algorithm Speed and Direction Prediction-based Localization (SDPL), which the preliminary version was previously published in [121]. The method allows localizing mobile sensor nodes with the assistance of a mobile anchor visiting the sensor area and following a path that ensures visiting the maximum number of nodes. Note that the mobile anchor is different from the sink as it is not permanently present in the network. In animal monitoring or disaster management applications [19, 132], especially in hostile areas, the mobile anchor could be a UAV sent to monitor sensor nodes, take photos and videos and other tasks. The algorithm is fully distributed since mobile nodes estimate by themselves their location information and independently from each other, which makes the mechanism very suitable for intermittently connected networks. The mobile anchor initially provides an initial location reference to mobile nodes by sending location beacons periodically. When receiving anchor location beacons, nodes use multilateration technique to estimate their positions. If nodes can no longer receive location beacons from the anchor, they continue estimating their positions independently from the anchor using our mobility-prediction scheme. The scheme exploits previous nodal locations to predict the speed and the direction a mobile node moves with. We refer the interested reader to [121] and to its improvement published in [131] for further details.

The choice of using SDPL as a localization algorithm is motivated by its ability to provide an estimation of the speed $\boldsymbol{V}$ and the direction angle $\boldsymbol{\theta}$ that a node is moving with and especially it provides an estimation of the localization error bound $\boldsymbol{\varepsilon}$. These three parameters are very important for our forthcoming routing approach.

2.1.1 Location Prediction

Suppose that node ***i*** has estimated its position at time t-1, P^{i}_{t-1}, as $(x^{i}_{t-1}, y^{i}_{t-1})$ along with an estimation of its speed, V^{i}_{t-1}, and its angle of orientation, θ^{i}_{t-1},. Then, node ***i*** can predict its position P^{i}_{t} at time t , as follows:

$$P^{i}_{t} = P^{i}_{t-1} + \overrightarrow{V^{i}_{t-1}} \times \Delta\,\mathrm{T}$$

$$\leftrightarrow \begin{cases} x^{i}_{t} = x^{i}_{t-1} + V^{i}_{t-1} \times \cos\theta^{i}_{t-1} \times \Delta\mathrm{T} \\ y^{i}_{t} = y^{i}_{t-1} + V^{i}_{t-1} \times \sin\theta^{i}_{t-1} \times \Delta\mathrm{T} \end{cases} \qquad (1)$$

where $\Delta\mathrm{T} = T_{t} - T_{t-1}$ and where the speed is calculated as

$$V^{i}_{t-1} = \frac{\sqrt{(x^{i}_{t-1} - x^{i}_{t-2})^{2} + (y^{i}_{t-1} - y^{i}_{t-2})^{2}}}{T_{t-1} - T_{t-2}} \qquad (2)$$

and θ^{i}_{t-1} representing the angle between the x-axis and the speed vector $\overrightarrow{V^{i}_{t-1}}$ at time t is estimated as

$$\theta^{i}_{t-1} = \tan^{-1}\left(\frac{y^{i}_{t-1} - y^{i}_{t-2}}{x^{i}_{t-1} - x^{i}_{t-2}}\right) \qquad (3)$$

2.1.2 Location Refinement

The idea of location refinement is to refine the estimated speed and direction angle based on the node's recorded historical information. In case node ***i*** has previously estimated ***n*** positions (***n*** is a constant representing the number of previous estimated positions a node is allowed to store), the prediction could be more refined. Node ***i*** calculates then the speed between each couple of consecutive stored positions following formula (2) and takes the average as its predicted speed V_t^i. As for predicting the direction angle θ_t^i , it will be calculated as the angle formed between the x-axis and the linear regression line that best fits the ***n*** positions. Once the speed and the direction angle are predicted, node ***i*** continues to use formula (1) to predict its current position until receiving again location beacons from the anchor that allow it to refine its estimation; and previous stored estimated positions will be erased and their counter will be initialized.

Recall that the applications we are targeting by our approach such as wild animal monitoring and environmental surveillance do not require high location precisions even though a more accurate location would be more appreciated. Due to the computing complexity of Kalman Filter for tiny sensors, we have chosen to apply the polynomial regression with least squares in SDPL motivated by its simplicity to implement and its reduced time processing. In fact, Kalman filter was found of time complexity of $O(N^3)$ while the least square (LS) is of complexity of $O(N^2)$ [133] thus LS is faster than Kalman filter. In addition, polynomial regression fits a non-linear model to the data even though the regression is linear so it can be applied in larger scenarios. Thus, in polynomial regression, the errors don't have to be Gaussian; they only need to be uncorrelated [134].

It is worthwhile to mention that we have improved the accuracy of SDPL, by an adapted selection function of the parameter ***n*** so that the linear regression line given by the least square approach fits with the adequate number of previous locations thus predicting more accurately the current location of a node.

The linear regression line of node ***i*** is defined by the line

$$y^i = a^i + b^i\, x^i \tag{4}$$

where

$$a^i = \frac{\sum_{j=1}^{n} y_j^i - b \sum_{j=1}^{n} x_j^i}{n} \tag{5}$$

$$b^i = \frac{n \sum_{j=1}^{n} (x_j^i y_j^i) - (\sum_{j=1}^{n} x_j^i)(\sum_{j=1}^{n} y_j^i)}{n \sum_{j=1}^{n} (x_j^i)^2 - (\sum_{j=1}^{n} x_j^i)^2} \tag{6}$$

where ($\boldsymbol{x_j^i}$, $\boldsymbol{y_j^i}$) are the coordinates of the location ***j*** among the ***n*** locations stored in node ***i***.

2.1.3 Location Error

There is always an error ε_t^i between the real position and the estimated position. Since node ***i*** is not aware of its real position, it can only have an estimation of its location error. Since nodes estimate their positions by themselves, their location errors are independent. The localization error of node ***i*** is defined as the distance between the estimated position and the real position of ***i*** and is calculated as:

$$\varepsilon_i = \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2} \tag{7}$$

Where (x_i, y_i) is the real position of ***i*** and $(\hat{x}_i, \hat{y}_i)$ is its estimated position.

In static networks, most of works concerned by location error tackled only measurement-induced errors, specifically GPS-induced errors [94]. These works assume that the location error in each node is independent and is generally modeled by a Gaussian distribution $N(\mu, \sigma^2)$ with zero mean ($\mu = 0$) and finite standard deviation . The variance of the Gaussian error on x-axis and y-axis for each individual node are assumed to be equal. The Gaussian probability function is given by:

$$f(x) = \left(\frac{1}{\sqrt{2\pi\sigma^2}}\right)\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \qquad (8)$$

The error ε_i of node ***i*** is supposed to follow a Rayleigh distribution with probability density function:

$$f(\varepsilon_i) = \frac{\varepsilon_i}{{\sigma_i}^2} e^{-{\varepsilon_i}^2/2\,{\sigma_i}^2} \qquad (9)$$

However, in mobile networks, few works considered the location errors, mainly GPS-induced errors [99] while works using mobility prediction used simulation experiments to deduce then a location error model [103, 104]. With GPS-free localization such SDPL, modeling the localization error becomes even a very complex task as it depends on many factors including the sources of location errors such as the uncertainty in anchor beacons, the RSSI-induced error, the unpredictable mobility of nodes and the localization algorithm itself which makes the location error harder to predict/mitigate [47].

For these reasons, and as nodes are GPS-free and knowing that our scheme proposes the use of a mobile anchor to initially help localizing mobile nodes and to help in refining nodes' location estimations, modeling the location error differ from proposed models which led us to perform an experiment using simulation to study and to approximate the location error. Through this study, we observed that the location error of each mobile node depends upon two main parameters, its velocity and the location update time interval. When the velocity increases the location error increases too and when the time between two estimations increases, the location increases too. By analyzing the results, we propose the following approximation formula for predicting the location error bound. Node ***i*** can estimate its own location error bound at time ***t*** by:

$$\varepsilon_t^i = \frac{\pi}{2}\left|\overrightarrow{V_t^i}\right| \times \Delta\mathrm{T} \times e^{-\frac{Vmin}{\Delta T}} \qquad (10)$$

where V_{min} is the minimum speed of nodes.

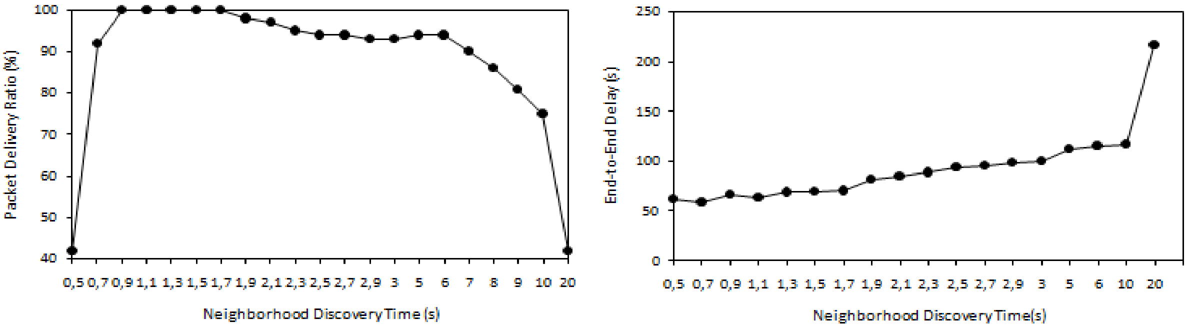
2.2 ROUTING ALGORITHM

In this section, we describe our proposed routing algorithm. It is mainly composed of two phases namely the On-Demand Mobility-based Adaptive Neighborhood Discovery and the Best Forwarder Selection. The neighborhood discovery is launched only when the packet holder needs to forward the packet, thus allowing saving more energy and wireless resources. The best forwarder selection relies on a new selection of metrics especially designed for mobile sensors taking into account the localization error, the speed and the direction of neighbors.

2.2.1 On-Demand Mobility-based Adaptive Neighborhood Discovery

Since nodes are mobile, exchanging periodically beacons between neighbors without packet forwarding (which is generally the case in most of proposed geographic routing protocols) consumes unnecessarily their energy and wireless resources [93]. Moreover, information obtained by long periodic beacon exchanges may not remain valid due to the mobility of nodes. This information invalidation becomes higher when the speed of nodes is high. Thus, it is more efficient for a mobile node to collect the position information of its neighbors only when it needs to forward a packet. This strategy has been successfully adopted by some geographic routing such as [69] and proved to be energy-efficient. The novelty of our approach is in proposing a function to evaluate the most adequate neighborhood discovery time interval that maximizes the delivery ratio.

Choosing a suitable time interval for neighborhood discovery is very important and can affect heavily the routing process. In one hand, if this interval is too long, then many forwarding opportunities may be missed [70], that is, the packet holder may miss many undiscovered neighbors which may be really good candidates to forward the packet, also this will lead to a long end-to-end delay as shown in Figure 1 (b). On the other hand, if this interval is too short, the packet holder will unnecessarily rediscover its previous neighbors since no much change happened but this will be done to the detriment of energy consumption of nodes when exchanging messages and will increase the overhead, which may lead to collisions and bandwidth wastage. To evaluate the impact of neighborhood discovery time on the routing efficiency, we conducted a study through simulation. Figure 1 shows the performance of INTEGER when varying the discovery time using the default values described in table 2.



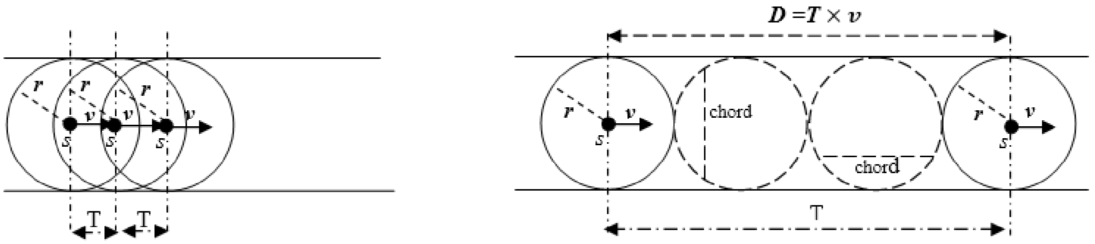
(a) (b)

Figure 1: Impact of Neighborhood Discovery Time.

Clearly, Figure 1 (a) shows that the delivery ratio reaches the peak at a given interval. The discovery time depends upon three parameters. The communication range (***r***) that defines the neighborhood region, the average number of neighbors per node (***N***) and the average speed of nodes (***v***). When this speed is unknown, we consider $v = \frac{\text{Vmax}}{2}$

To calculate the suitable discovery time (***T***), we suggest the following :

To determine the lower and upper bounds of ***T***, one considers the illustration in Figure 2 that shows examples of overlapping and non-overlapping communication areas of node ***s*** at successive neighborhood discoveries. The discontinued circles represent virtual undiscovered areas between two neighborhood discoveries.



(a) (b)

Figure 2: Overlapping and non-overlapping areas at successive neighborhood discoveries.

To determine the upper bound, consider that the areas covered by s at each discovery do not overlap as shown in the example of Figure 2 (b), then the average number of missing neighbors during T is:

$$Nmiss = N \times \frac{T}{Tch} \qquad (11)$$

where Tch is the average time needed for a neighbor to pass the chord of the circle representing the communication area of s as represented in Figure 2 (b). We have chosen the chord as a reference, as it is the average distance that a neighbor travels while being in the communication area of the packet holder.

The average length of the chord of a circle is given by

$$Chord\ Lenght = \frac{4r}{\pi} \qquad (12)$$

Thus, $Tch = \frac{Chord\ Lenght}{v}$, from (9), $Tch = \frac{4r}{\pi v}$ (13)

From (11) and (13), $Nmiss = \frac{N \times T \times \pi v}{4r}$ (14)

In order for s to not miss any neighbor, $Nmiss < 1$ (15)

From (14) and (15) : $\frac{N \times T \times \pi v}{4r} < 1 \rightarrow T < \frac{4r}{N \times \pi v}$ (16)

To determine the lower bound of T, consider that the areas covered by s at each discovery overlap as shown in the example of Figure 2 (a). In order for s to discover at least one new neighbor in the next discovery, s should displace at least by $\frac{r}{N}$.

Thus : $T \times Vmax > \frac{r}{N}$ (17)

From (17): $T > \frac{r}{N \times Vmax}$ (18)

From (16) and (18) : $\frac{\boldsymbol{r}}{\boldsymbol{N \times Vmax}} < T < \frac{\boldsymbol{4\,r}}{\boldsymbol{N \times \pi v}}$ (19)

To select a new forwarder, the packet holder proceeds first to neighborhood discovery. To do so, it broadcasts a ***Position_Request*** message to nodes within its transmission range for requesting neighbor position information. Once a neighbor node receives this message from the sender, it replies with a ***Position_Response*** message containing its estimated position information including the estimated coordinates ***(x, y)*** with an error bound $\boldsymbol{\varepsilon}$, its estimated speed ***V***, and its estimated angle of orientation $\boldsymbol{\theta}$. Based on these data, the packet holder builds a temporary neighborhood table from which it selects its best forwarder.

2.2.2 Best Forwarder Selection

In this section, we describe the principle of our best forwarder selection and the parameters to consider when making routing decisions. As presented in chapter 2, nodes' directions can jeopardize the greedy forwarding. From this perspective, we propose to consider the direction of neighbors in the forwarder selection.

The best forwarder will be chosen among the neighbors that go in the direction towards the sink. Before sending a packet, the source node assigns a direction to the packet called *packet direction* so that only nodes having the same moving direction as the packet direction will be candidates to route the packet to its destination. To determine the packet direction, the source calculates the current angle θ that forms with the sink and assigns to the packet a direction number **"$\boldsymbol{\rho}$"** among the four possible directions shown in Figure 3. Depending on the range of θ, **"$\boldsymbol{\rho}$"** is associated to the packet and will be considered as the *packet direction*. If the sink is static, the packet direction remains the same during the whole packet travel. If the sink is mobile, then each packet holder assigns a new packet direction depending on the current sink location and embeds it in the packet header. The number **"$\boldsymbol{\rho}$"** that identifies the packet direction is associated to each direction following function (20).

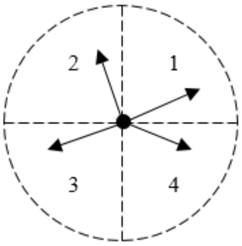


Figure 3: The four possible directions.

$$\begin{cases} 0 < \theta \le \frac{\pi}{2} \leftrightarrow \rho = 1, \\ \frac{\pi}{2} < \theta \le \pi \leftrightarrow \rho = 2, \\ -\pi < \theta \le -\frac{\pi}{2} \leftrightarrow \rho = 3, \\ -\frac{\pi}{2} < \theta \le 0 \leftrightarrow \rho = 4. \end{cases} \tag{20}$$

Note that this identification of directions serves also to assign a direction number to mobile nodes so to make easy the comparison between the packet direction and the current direction of a candidate. In this case, $\boldsymbol{\theta}$ will be the estimated angle of orientation of node $\boldsymbol{x_i}$ given by SDPL method at time $\boldsymbol{t}$. The main difference between the packet direction and node direction numbers is that the packet direction is calculated considering the angle that a source forms with the sink at the time the packet generation independently from the current source direction. However, a node direction is calculated considering the angle of orientation that a node moves with, independently from the sink.

If the direction number of a neighbor $\boldsymbol{x_i}$ is the same as the packet direction, then $\boldsymbol{x_i}$ is a candidate, otherwise $\boldsymbol{x_i}$ is not going towards the sink. Note that the case in which the angle between the source and the sink is very close to the lower or the upper bound of θ in function (20) is critical, as among nodes belonging to the previous or next direction may be good candidates. In this case, we apply the *right-hand-side* rule used in conventional geographic routing protocols to choose only one direction.

Figure 4 shows an example of how a source node determines the packet direction and how to know the direction numbers of its neighbors. In this example, and according to the four possible directions, only $\boldsymbol{x_2}$ will be a candidate since it has the same direction number as the packet direction number (which is number 4 in the example of Figure 4).

Once a sender has received ***Position_ Response*** from its neighbors; it builds a temporary neighborhood table and associates to each neighbor a weight calculated based on the received location information from neighbors.

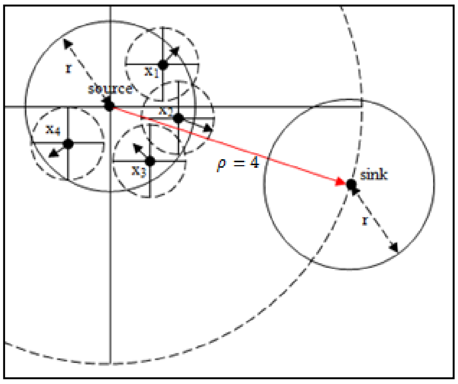


Figure 4: Selection based on the packet direction and neighbors' directions.

The weight measures a node's aptitude to forward efficiently a packet. The packet holder selects then the neighbor that has that has the highest weight among the neighbors that have the same direction number as the packet direction. The neighborhood table is as follows:

Table 1 Temporary Neighborhood Table

Estimated **(x, y)**	Estimated **(V, θ)**	Localization Error **ε**	Weight **W**	Direction Number **ρ**

Thus we can formally define the best forwarder F as:

$$\mathbf{F} = \{\mathbf{F} \in \mathbf{Ns} \mid (\boldsymbol{W_F} = \max_{i \in Ns} \boldsymbol{W_i}) \cap (\boldsymbol{W_F} > \boldsymbol{W_S}) \cap (\boldsymbol{\rho_F} = \boldsymbol{k})\} \qquad (21)$$

where Ns is the set of the neighbors of the sender node ***s*** and ρ_F is the direction number of neighbor ***F*** and ***k*** is the packet direction. The weight of each node is calculated using the following formula:

$$W_i = \begin{cases} \frac{V_i \times Drss_i}{ED_i \times \varepsilon_i}, & i \neq s \\ \\ \frac{V_i \times R}{ED_i \times \varepsilon_i}, & i = s \end{cases} \qquad (22)$$

where $\boldsymbol{V_i}$ is the estimated speed of a neighbor ***i***, $\boldsymbol{Drss_i}$ is the distance between node ***i*** and the sender based on the received signal strength, $\boldsymbol{ED_i}$ is the distance between the estimated position of the neighbor ***i*** and the Destination, $\boldsymbol{\mathcal{E}_i}$ is the localization error bound of a neighbor ***i***. In order not to fall in a loop selection, the packet holder calculates its weight considering the ***Drss*** as its radio range ***R*** as mentioned in formula (22).

In formula (22), the speed is in the numerator so that neighbors with higher speed will be favored. The converted distance from the RSSI is also put in the numerator to favor the farthest neighbors of the sender. Even if the farthest neighbors of the sender might not be the closest to the destination but favoring also the shortest estimated distance between a neighbor and the destination can balance the total weight of a node. The localization error is in the denominator to favor candidates with low localization error thus their communicated data are more trusted. Because all the other metrics are estimated, RSSI distance can balance the formula by bringing certain exactitude to the formula.

In formula (22), $\frac{V_i}{ED_i}$ can be seen as $\frac{1}{ET_i}$ where ET_i is the estimated delay for a packet to virtually travel the direct link between node ***i*** and the destination. This delay can be considered as a *Quality of Service (QoS) factor* for node ***i***. The smaller this delay, the higher is the weight of a node. $\frac{Drss_i}{\varepsilon_i}$ can be considered as a *link reliability factor* for node ***i***. The higher this factor, the higher is the weight.

Note that neighbors that are not in the progressive area (grey area in Figure 5) going towards the destination could be also candidates even if they are farther to the destination than the packet holder, i.e. behind the sender. The main reason to not exclude these neighbors, as greedy forwarding does, is that among them, it may be a good forwarder going towards the destination and with higher speed than the current packet holder thus resulting in having a higher weight than the packet holder. Figure 5 shows a similar case where x_4, and despite being farther from the destination than the packet holder ***s***, it moves with a higher speed than ***s*** and with the same direction as the packet direction (the length of the red arrows represents the velocity magnitude). Thus, it can forward the packet quicker than ***s***, which makes it good candidate.

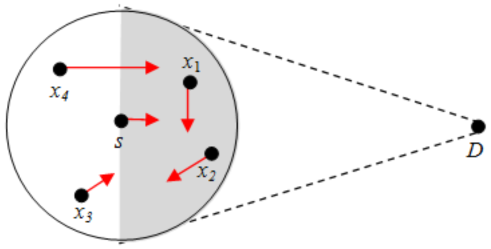


Figure 5: Candidate selection favoring the speed.

Algorithm 1 summarizes the best forwarder selection paradigm.

Algorithm 1: Best Forwarder (i, Ni, k, Destination)

```
// i is the packet holder,
// Ni is the set of neighbors of node i
// k is the packet direction number
Begin
  F ← i
  $W_i = \frac{V_i \times R}{D(i,d) \times \varepsilon_i}$
  For each N ∈ Ni do
    $\theta$ ← SDPL direction angle (N)
    $\rho$ ← Direction Number ($\theta$) //Calculated according to formula (20)
```

```
        $W_N = \frac{V_N \times Drss\,(N,i)}{D(N,d) \times \varepsilon_N}$
        if ($W_N > W_i$ and $\rho = k$)
            F ← N
            $W_i \leftarrow W_N$
        end if
    end do
    return F
End
```

Figure 6 shows an example of selecting the best forwarding considering the different neighboring parameters. Let ***s*** be the sender node, x_1 and x_2 are its neighbors that have the same direction as the packet direction (red arrows in Figure 6 show that they are in direction 1 as ***s-D*** link). In other words, they are candidate to be forwarders. ***(s, x_1, x_2)*** are their real positions respectively while ***(s', x'_1, x'_2)*** are their estimated positions that they communicate to the packet holder. $(\boldsymbol{\varepsilon_s}, \boldsymbol{\varepsilon_1}, \boldsymbol{\varepsilon_2})$ are their location-error bounds. sx_1, sx_2 are distances between the sender and x_1 and x_2 respectively. These distances are converted from the received signal strength indicator while receiving position response from the neighbors. ED_1 and ED_2 are the estimated distances between the neighbors and the sink. ***(Vs, Vx_1, Vx_2)*** are their estimated speeds respectively. The packet holder compares between the neighbors' weights and its self-weight. The neighbor that has the highest weight with the same direction number as the packet direction will be selected as the best forwarder.

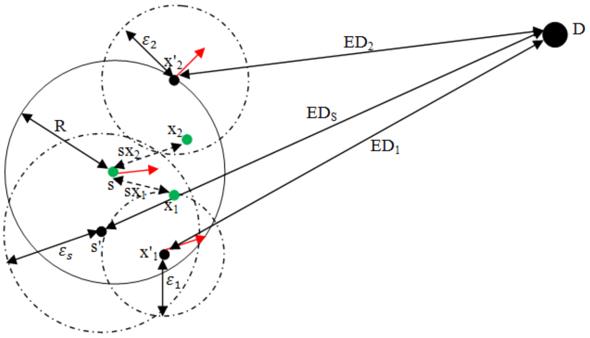


Figure 6: Candidate selection considering different parameters

Numerical Example: In the previous example, let the estimated speed of node x_1 be 7m/s and that of x_2 be 5m/s. let the estimated distance between x_1 and the sink be 75m and that between x_2 and the sink be 60m. Accordingly, x_1 is far from the sink than x_2. The D_{rss} that ***s*** has converted from the received signal of x_1 is 15m and that from x_2 is 20m. The localization error bound of x_1 is estimated to be 10m while that of x_2 is 20m. The location information of ***s*** is as follows: the estimated speed is 3m/s, the estimated distance between ***s*** and the destination is 85m and its error bound is 25m. The communication range is 30m. According to MFR strategy, ***s*** believes that x_2 is its best forwarder. However, by applying Formula (22), $W_1 = 0.14$ and $W_2 = 0.08$. $Ws = 0.04$. The sender forwards then the packet to x_1 and destroys the neighborhood table after receiving an acknowledgment from x_1 to save its memory.

We give priority to nodes with higher speed values and with minimal error bound. Consider the following example: Let x_1 and x_2 have the same speed 6m/s. $W_1 = 0.12$ and $W_2 = 0.10$. Then, x_1 will be chosen since it has the lowest error bound because it is more credible even if it believes that it is farther from the sink than x_2.

Equally, if the x_1 and x_2 have almost the same error bound 15m but with different speeds, x_1 with 7m/s and x_2 with 10m/s.

W_1= 0.09 and W_2=0.22. Then, x_2 will be chosen since there is high probability that it reaches the sink before the x_1 even though they have the same location error bound.

If the packet holder finds no neighbor that goes towards the sink or no neighbor that has higher weight than its weight, i.e. no neighbor fulfills condition (21), then it applies the *carry-and-forward* strategy, that is, it keeps holding the packet while continuing its basic trajectory hoping to across a neighbor that goes toward the destination or being in a more adequate neighborhood.

In the previous example, if s moves with 12m/s which higher than the speeds of its neighbors, then Ws=0.16 > W_1=0.14 > W_2=0.08. Thus, s has the highest weight, which makes it more appropriate to route quickly the packet.

Same case if the location error bound of s is smaller than the errors of its neighbors. Let it be 5m, then Ws=0.21> W_1=0.14 > W_2=0.08. Thus, s has the highest weight because its location data are more trustful. Therefore, keeping the packet is wiser than forwarding it.

2.2.3 Local Maximum Handling

Sometimes, there is no neighbor having a weight superior than the weight of the packet holder, in this case, while keeping the packet, the packet holder checks then for a new neighborhood each time T (as calculated in formula 19). Once a best forwarder has been selected, the packet holder sends the packet to this selected node, keeps a copy of the packet and waits for the reception of an acknowledgment. Sometimes, for some reasons, such as collisions, the selected best forwarder cannot receive the packet, thus the sender will not receive any acknowledgment. In this case, once the duration for receiving the acknowledgment expires, the sender anew launches the neighborhood discovery and the best forwarder re-selection, which may result in choosing the same forwarder or another forwarder due to mobility change. The process of forwarding is then repeated until the packet reaches the destination. Algorithm 2 explains the behavior of a packet holder i during the forwarding process.

Algorithm 2: Forward (i, pk, Destination)

```
// Initialization executed at the time of packet generation
if ($i \in S$) // S is the set of source nodes
    Pk ← Packet
    $\varphi$ ← Current angle between node i and Destination
    k ← Direction Number ($\varphi$) //Calculated according to formula (20)
end if
Begin
Ni ← Neighborhood Discovery (i)
F ← Best Forwarder (i, Ni, k, Destination)
if (F = i)
```

```
5:        i keeps pk for T
6:        go to (2)
7: else
8:     Send Packet Pk to F
9:     Destroy Table of neighborhood
10:    Wait for Ack from F
11:      if no ack received from F
12:        go to (2)
13:     end if
14: end if
15: End
```

So instead of just sending a packet to its best forwarder, in our approach, the sender makes sure the packet is well received by the best forwarder otherwise it tries to find another forwarder able to receive the packet. This could be very efficient especially in highly dynamic networks where nodes that were not considered best forwarders in the past may become it in the next neighborhood discovery due to their mobility change, which may play in their favor. This strategy of keeping the packet and re-selecting another forwarder allows saving packets from being dropped or lost. Our simulations confirmed this gain. When considering default values in table 2, we found out that this re-selection strategy increases the delivery ratio by up to 30% as shown in Figure 7.

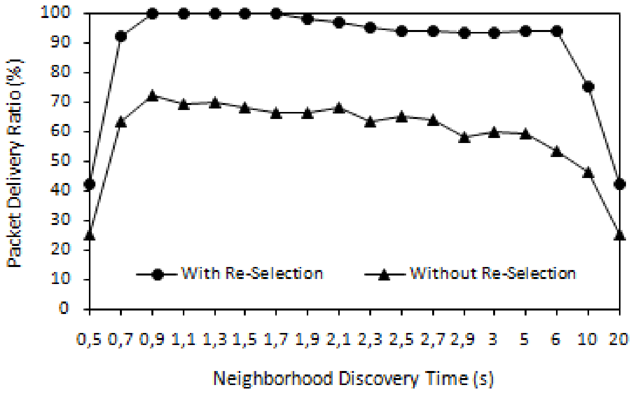


Figure 7: Impact of re-selection strategy on Delivery Ratio

2.2.4 Loop Handling

Note that it is possible that a given node x_i can be chosen as the best forwarder even though it has previously forwarded the same packet. This is because of x_i's mobility change. x_i can move to a more suitable new location or increase its speed that may be considered by the current packet holder as favorable using our forwarding scheme. Unlike the traditional loop formed in static networks, we believe this case of *re-use* can be productive as long as it helps achieving progress to forward the packet towards the destination. Figure 8 shows an example where node x_1 has been chosen again as the best forwarder by the packet holder. At time t_1 the packet holder s_1 chooses x_1 as its best forwarder according to our best forwarder selection strategy. At time t_n the current packet holder s_n again chooses x_1 as its best forwarder as it's the one that fulfills condition (21). Hence x_1 has participated again in the routing process of the same packet towards the destination D.

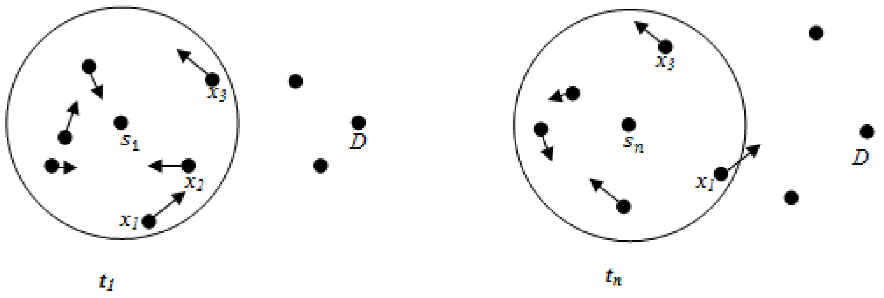


Figure 8: case of re-use of a forwarder.

2.3 Properties and Comparison

In this section, we present the main properties of INTEGER. As for comparison, we decided to compare INTEGER with MAGF [89], GPSR-MS [86] and GPSR [75]. The choice of MAGF was motivated by its utilization of the store and forward strategy. When a node cannot find a better forwarder than itself, it carries the packet until finding a better neighbor to advance the packet towards the destination. In addition, MAGF exploits the mobility pattern of nodes to select the best next-forwarder as INTEGER does. The main differences between MAGF and INTEGER are that the former supposes that the exact location of nodes and their mobility including their speed and direction are known, which is not the case for INTEGER that relies on the prediction of nodes locations including predicting their speeds and directions. MAGF applies the objective function as a backup and only for neighbors behind the sender while the objective function of INTEGER applies to all neighbors. GPSR-MS also exploits the node mobility pattern and involves the current speed of nodes and evolution in distances in the objective function. GPSR was chosen as a baseline reference.

Property 1. INTEGER selects more reliable candidates than its concurrents.

Proof: consider the objective function of each proposal:

$$OF_{GPSR} = D(i,d) \qquad (23)$$

$$OF_{GPSR-MS} = \frac{D_p(i,d) \times D_p(i,d)}{D_n(i,d) \times v_i} \qquad (24)$$

Where $D_p(i,d)$ is the previous distance between node i and destination d, while $D_n(i,d)$ is the new one. The fraction of these two distances is considered by the authors as the direction of node i.

$$OF_{MAGF} = \begin{cases} D(i,d) & if\ D(i,d) < D(s,d) \\ MP\ (i,d) & otherwise \end{cases} \qquad (25)$$

Where $MP\ (i,d) = \begin{cases} 1 + \frac{v_i}{\cos\theta \times D(i,d) - \sqrt{R^2 - (\sin\theta)^2 \times D(i,d)^2}} & if\ 0 \leq \theta < \sin^{-1}\frac{R}{D(i,d)} \\ \frac{\theta}{2} & \sin^{-1}\frac{R}{D(i,d)} \leq \theta \leq \pi \end{cases}$ (26)

Where θ represents the angle formed by the line segment connecting node *i* and destination *d*, and the current motion vector of node *i*.

Unlike its concurrents, INTEGER considers in the candidate weight the distance between the sender and a candidate; this is to ensure the link quality during data transfer especially in high dynamic scenarios. While the other approaches do not consider such metric. In addition to the consideration of location errors in the forwarder selection which is unique to INTEGER. As mentioned earlier, $\frac{\mathrm{Drss_i}}{\varepsilon_i}$ is considered as reliability factor.

Property 2. INTEGER makes efficient progress toward the destination.

Proof: INTEGER selects only candidates going toward the destination and with higher speeds while GPSR doesn’t consider the moving speed at all, GPSR-MS favors also higher speeds but the approach how a sender perceives the direction a candidate is moving with, is not reliable. Authors considered a node is going toward the destination if its new distance to the destination is smaller than the previous one; which is not always the case as a node may move to a position closer to the destination but is going completely toward other direction. In addition, authors consider a node is static if the new distance to the destination is equal to the previous one, which is not always the case.

As for MAGF, the motion potential objective function that considers the speed and the direction of a candidate is applied only as a backup if the greedy forwarding fails which means in the default case only the distance between a candidate and the destination is considered to select the forwarder.

Property 3. INTEGER guarantees the delivery of the packet.

Proof: thanks to its strategy of re-selection of the best forwarder in case of failure of reception by the chosen forwarder, INTEGER guarantees the delivery of a packet. The main concern becomes then when the packet arrives at its destination and the energy needed to deliver it successfully. While for the concurrent approaches, a packet is dropped if a neighbor failed to receive the packet.

3. PERFORMANCE EVALUATION

3.1 SIMULATION SCENARIOS AND METRICS

To evaluate our proposed protocol INTEGER, we have implemented it in NS2 simulator [143] which is widely used in academic network researches.

We consider networks with *n* nodes, where *n* = 100 by default. Initially, the sensors are randomly and uniformly deployed in a square area of size 200 × 200 m². The default transmission range ***r*** is set to 30m. Therefore, the network degree ***d*** is around 7 according to defined in [1]:

$$\mathrm{d} = \frac{n\,\pi\,r^2}{\mathrm{A}} \qquad (27)$$

where A is the sensor communication area.

We decided to show results when the number of sources is set to 10 sources (10% of nodes) because using less than this number of sources, the packet delivery ratio of our proposal was observed to be always 100% for all scenarios. Thus, the comparison with other protocols would not be significant. Data traffic is generated according to a Poisson process of intensity $\boldsymbol{\lambda}$ packets per second over the whole network. The traffic rate $\boldsymbol{\lambda}$ varies from 0.25 to 2 packets per second. Data packets are all 256B long. We randomly choose 10 source nodes while we keep the sink static and located at the center of the area. Mobile nodes follow the Random Waypoint (RWP) mobility model with no pause time. The maximum speed of nodes ranges in {3, 5, 10, 15} m/s while the minimum speed is 0.05 m/s to ensure that all nodes are totally mobile. The mobile anchor that assists the localization phase follows *WAVES* trajectory [20] with a resolution of 20m and has a fixed speed of 20m/s emulating UAV average speed. Each 6 seconds, nodes independently estimate their positions. The routing phase starts after 100s of the execution time to let nodes use the localization prediction. All our results have been obtained by averaging the outcomes of 50 independent simulations; each running for 1000 s. Table 2 summarizes the parameters ranges and the default values.

To analyze the simulation results, the main metrics chosen are the packet delivery ratio, the packet delivery delay, the number of relay nodes per packet and the consumed energy per packet. The packet delivery ratio, defined as the fraction of packets that are successfully delivered to the sink; and the delivery delay, defined as the time from packet generation until its delivery to the sink. The number of relay nodes is the number of nodes participating in the routing process to deliver successfully a packet to the sink.

Table 2 Simulation Parameters for INTEGER

Parameters	Range	Default value
Area Edge Length	{100,150,200,250,300}	200m
Number of Nodes	100	100
Transmission range r	{20, 25, 30, 40, 60}m	30m
Nodes Degree d	[3.14- 28.26]	7.07
Packet generation rate PGR	[0.05- 2]	0.1
Mobility Model	RWP	RWP
Pause Time	0s	0s
SDPL Location Estimation Interval ΔT	6s	6s
Maximum speed of nodes V_{max}	{3, 5, 10, 15}m/s	5m/s
Minimum speed of nodes V_{min}	0.05 m/s	0.05 m/s
Data Packet Size	256B	256B
Number of sources	10	10
Simulation time	1000s	1000s

The per packet energy consumption, defined as the average amount of energy expended by all nodes to successfully deliver a packet to the sink and is calculated by

$$Energy = E_{Idle} + E_{Sleep} + E_{Tx} + E_{Rx} + E_{Trans} \qquad (28)$$

where E_{Idle}, E_{Sleep}, E_{Trans} is the energy spent during the idle, sleep and transition states respectively. E_{Tx}, E_{Rx} is the energy necessary for transmitting and receiving packets respectively.

The latter metrics are computed only for successfully delivered packets. When varying the localization error, we consider the average localization error of all sensors over the whole execution time. The mean error of all nodes is calculated each 6 seconds and the localization error is averaged at the end of the simulation.

We conducted a series of tests. The first set concerns the study of the impact of the nodes' speed on the delivery ratio, the end-to-end delay and the average number of relay nodes as well as the consumed energy of the compared protocols. In the second set, we vary the packet generation rate and we study its impact on the above metrics. The variation of the localization error is also studied to proof the error-resilience nature of our approach. We finish the tests with studying the effect of the network degree on the compared protocols.

3.2 PERFORMANCE COMPARISON

For simulation comparison, we compare INTEGER to its concurrents namely MAGF, GPRS-MS and GPRS. Note that none of the compared protocols basically used the mobility-prediction based localization; all considered the exact location without mentioning how this exact location is obtained. In contrast, the mobility-prediction based localization is a main component of our approach and considering the localization errors in routing decisions together with predicted mobility patterns is part of our contribution. For this reason and in purpose of doing an objective comparison between the four protocols, we associated our location-prediction scheme and the carry and forward strategy as well as the re-selection approach to the concurrent protocols. Thus, the comparison will be judged according to how successful the selection of the next-forwarder is and the impact of the consideration of the localization error in routing decisions. As for MAGF, the cache time was set to a value that ensures for the packet holder to carry the packet until finding a suitable neighbor.

3.3 SIMULATION RESULTS

3.3.1 Impact of the speed

In applications such as monitoring animals or weather monitoring relying on people/vehicles, the speed of individuals may vary without knowing the exact moving speed but only their maximum speed. The maximum speed can be derived from their biological/industrial nature or the congestion of roads taken. In this test, we vary the maximum speed of nodes between 3 m/s which represents the average human/animal walking speed and 15 m/s which represents the average driving speed of vehicles in urban agglomeration or the average running speed of wild animals.

Figure 9 (a) shows the packet delivery ratio when the maximum speed of nodes varies. Clearly, INTEGER outperforms the other protocols.

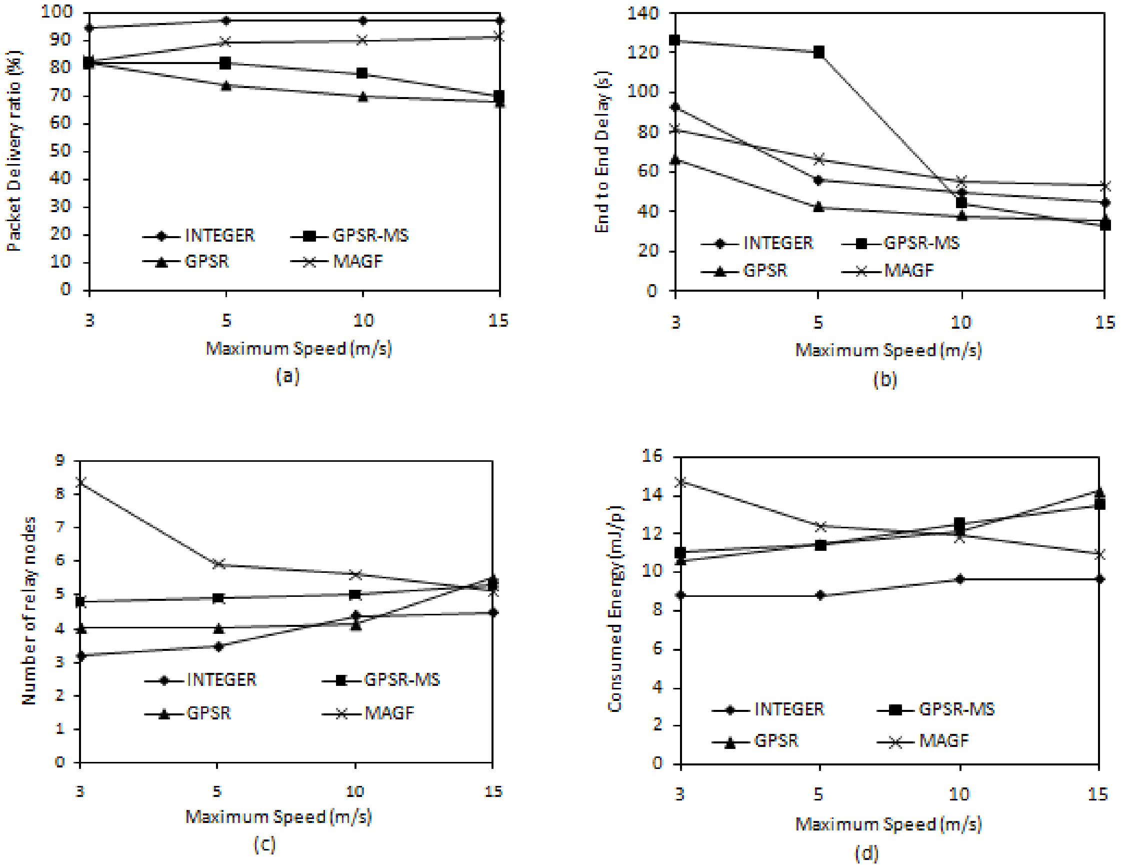

(a) (b) (c) (d)

Figure 9: **a** Packet delivery ratio vs. maximum speed. **b** End-to end delay vs. maximum speed. **c** Number of relays vs. maximum speed. **d** Consumed energy vs. maximum speed

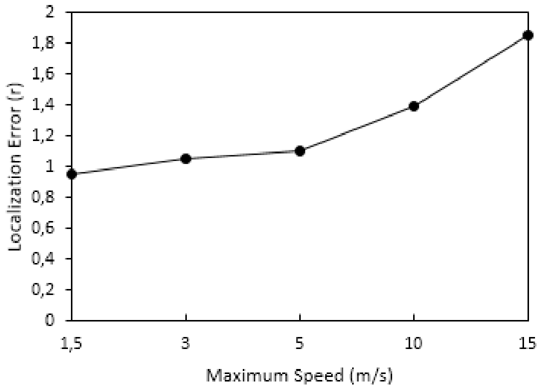


Figure 10: Localization Error vs Maximum Speed

We notice a tendency towards stability for INTEGER, thus less affected by the speed' increases. This is due to its strategy that supports the speed variations and localization errors caused by the increase of nodes' speeds. The improvement brought by INTEGER compared to MAGF is between 7% and 12%, while compared to GPSR-MS and GPSR the improvement is in the range of 12% and 28%. It is important to mention that INTEGER and MAGF have both a behavior different from the one of GPSR-MS and GPSR when varying the speed of nodes. While the delivery ratio increases for the two first protocols when increasing the speed, it decreases for the two last protocols. This attests that considering efficiently the mobility pattern of mobile nodes can improve much the routing efficiency by selecting the best next-forwarder. It is worth to mention that with the increase of nodes' speed, the localization errors increase too as shown in Figure 10. The consideration of localization errors by INTEGER when making routing decisions proves its eligibility and assets that the location errors should not be ignored or taken lightly. Since GPSR is based only on geographic advancement, the nodes tend to pick less reliable relays; this explains why GPSR gives the worst results.

As for the end-to-end delay, clearly, Figure 9 (b) shows that when nodes move with low speeds, this influences the packet delivery delay because of the carry and forward strategy. In other words, the packet speed depends on nodes' speeds. The higher the speed of the nodes, the lower the end-to-end delay. In addition, INTEGER tries always to choose the best combination of the most influencing factors (speed, direction, location error and distance toward the destination) to select the best forwarder. Before achieving this refined selection, the packet holder keeps carrying the packet with its own moving speed. Besides, GPSR and GPSR-MS have less constraints choosing the next-forwarder which leads them to make quick decisions but to the detriment of the packet delivery success. Figure 9 (c) shows the average number of relay nodes per successfully delivered packet. Our approach of considering the mobility pattern together with localization errors allows INTEGER to use less and well-chosen relay nodes to transmit packets. The number of relay nodes participating in the packet transmission slightly increases when increasing the mobility speed because of the frequent change of the neighborhood thus meeting new candidates. The same behavior is observed for GPSR-MS. GPSR shows a steady behavior between 3m/s and 10m/s while its curve heightens for 15m/s as GPSR works bad in highly mobile networks. As for MAGF, a decrease in the number of relay nodes is observed when increasing the speed of nodes but still this number is higher compared to other protocols.

The consumed energy per received packet is shown in Figure 9 (d). INTEGER shows a quite steady curve and widely outperforms other protocols evaluated while the energy consumed by MAGF decreases when the speed increases. As shown in Figure 9 (b), the packet speed is proportional to the node's speed, and because INTEGER and MAGF give the better results in terms of packet delivery, they tend to deliver the overall amount of packets generated by the sources in a relatively short time compared to GPSR and GPSR-MS, which makes nodes take a transmission-break after finishing transmitting all the packets thus consuming less energy. However, it is not the case for GPSR and GPSR-MS where it was observed that the delivery ratio lowers when increasing the nodes' speed because lot of packets travel the network hopping from node to node without reaching the destination thus consuming more energy.

3.3.2 Impact of the packet generation rate

Now we set the speed to 5m/s which represents a moderate speed and we vary the packet generation rate PGR generated by each source node.

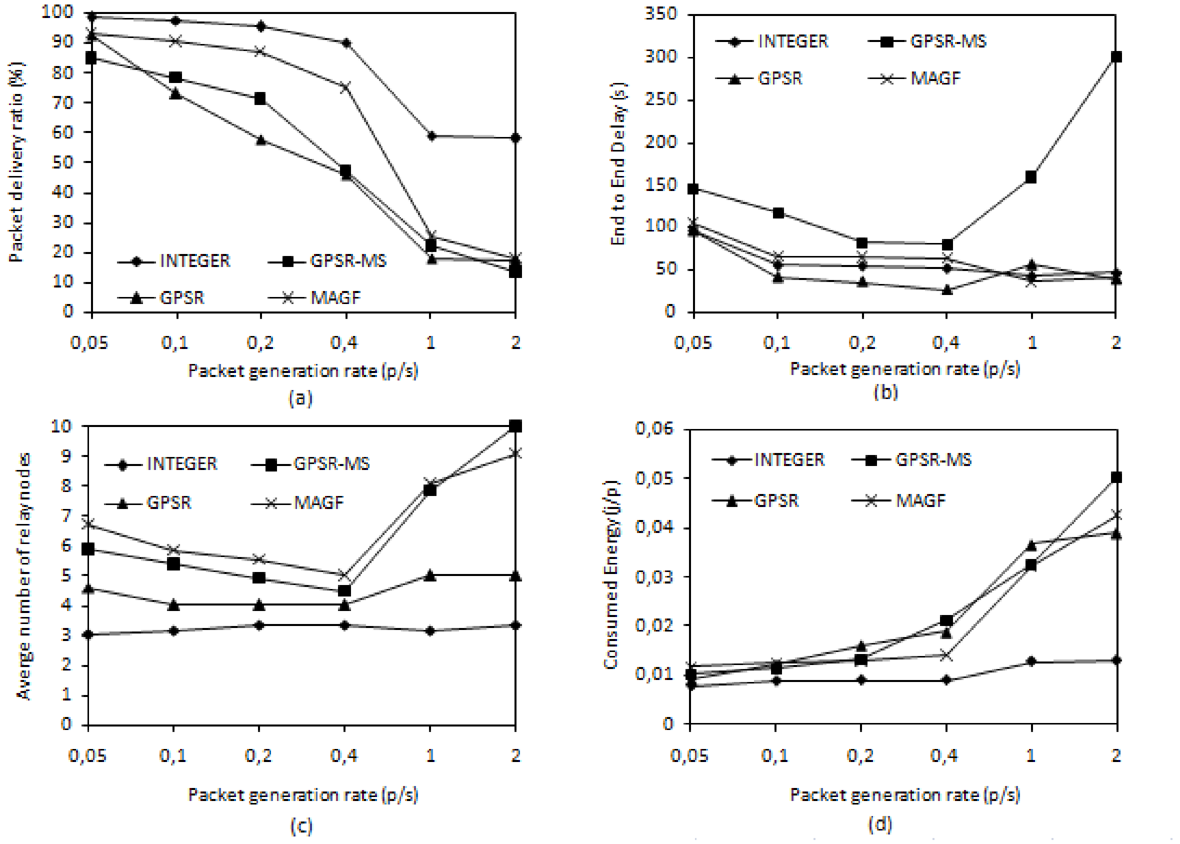


Figure 11: **a** Packet delivery ratio vs. PGR. **b** End-to-end delay vs. PGR. **c** Number of relay nodes vs. PGR. **d** Consumed energy vs. PGR

Figure 11 (a) shows that our proposed INTEGER widely outperforms other protocols especially when the packet traffic is higher. The improvement brought by INTEGER can reach 70%. All the curves show a decreasing behavior in the packet delivery ratio when increasing the traffic in the network. This is mainly because of the occurrence of collisions. In fact, the higher the traffic in the network, the more the collisions occur due to using only one channel. Note that without our strategy of re-forwarding after collision applied to all protocols in case of no acknowledgment is received, the delivery ratio is worse especially for GPSR, GPSR-MS and MAGF. INTEGER keeps the highest ratio even when the traffic is high and with relatively good end-to-end delay compared to the ones given by MAGF and GPSR as shown in Figure 11 (b) while using the minimum number of relay nodes as shown in Figure 11 (c). The per packet consumed energy of INTEGER as shown in Figure 11 (d) is the lowest one among the four protocols. All these results prove that our best forwarder selection scheme improves much the efficiency of the routing process and allows selecting the most adequate forwarder. As for the other protocols, nodes consume more energy and higher delay when trying to re-launch the forwarding selection and re-forward the packet to the new selected forwarder even if the latter is not available to receive more packets due to traffic congestion in the network.

3.3.3 Impact of the localization error

In this test, we intentionally vary the localization error resulted from the location-prediction to study its effect on the proposed geographic routing. The default values are applied.

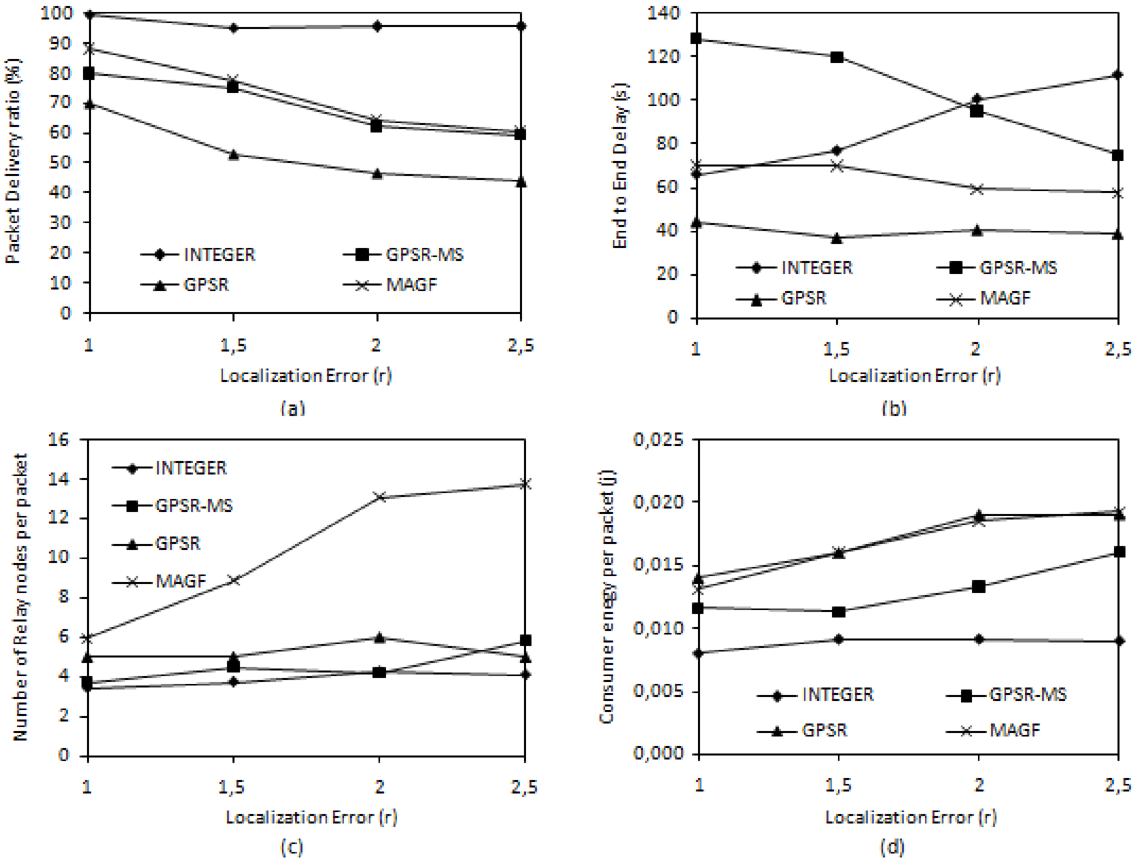


Figure 12: **a** Packet delivery ratio vs. error. **b** End-to-end delay vs. error. **c** Number of relay nodes vs. error. **d** Consumed energy vs. error

As we can notice, INTEGER gives the best results for most of the metrics. This is mainly because INTEGER considers the localization error while making routing decisions. Nodes with less location error are always favored to be next forwarders because they are more reliable and trusted. The degradation in the delivery ratio is minimal as shown in Figure 12 (a) while the average number of relay nodes is slightly increasing and so the consumed energy. However, Figure 12 (b) shows that the end-to-end delay per successful packet is very sensitive to the location-error. We explain that by the need for nodes to carry the packet for additional time until finding a suitable forwarder with less location-error. As for MAGF, the delivery ratio decreases when increasing the location-error and the degradation is noticeable while the consumed energy and the number of relay nodes increase sharply because nodes try hopelessly to find suitable forwarders but because of the high location-error, those forwarders are erroneously declaring being suitable and so will be erroneously selected which leads sometimes to distant the packet from the destination. Consequently, nodes will be obliged to reselect and find other more suitable forwarders. Because many nodes participate in the routing process in MAGF, this leads to more energy consumption. Meanwhile, we notice that the end-to-end delay given by MAGF slightly decreases. We explain that by the proportionality between the delay and the number of successfully delivered packets since the shown end-to-end delay is given for only successful delivered packets. Same explanation would be given for GPSR-MS and GPSR. Note that GPSR gives the lowest end-to-end delay but to the detriment of poor packet delivery ratio.

3.3.4 Impact of nodes' degree

We mean by the nodes' degree, the average number of neighbors per node. The node degree is a very important parameter since together with the mobility pattern, it determines how well connected nodes are. Note that according to formula (27), the obtained results are similar when changing the number of nodes in the network or the area length or the communication range. In fact, the results are equivalent if we vary the number of nodes in the set {45, 70, 100, 180, 400} or the length of the sensor area in {350, 250, 200, 150, 100} m. For simulation simplicity, we chose to vary the communication range of nodes in the set {20, 25, 30, 40, 60} which will give a node degree in the set {3, 5, 7, 13, 28}.

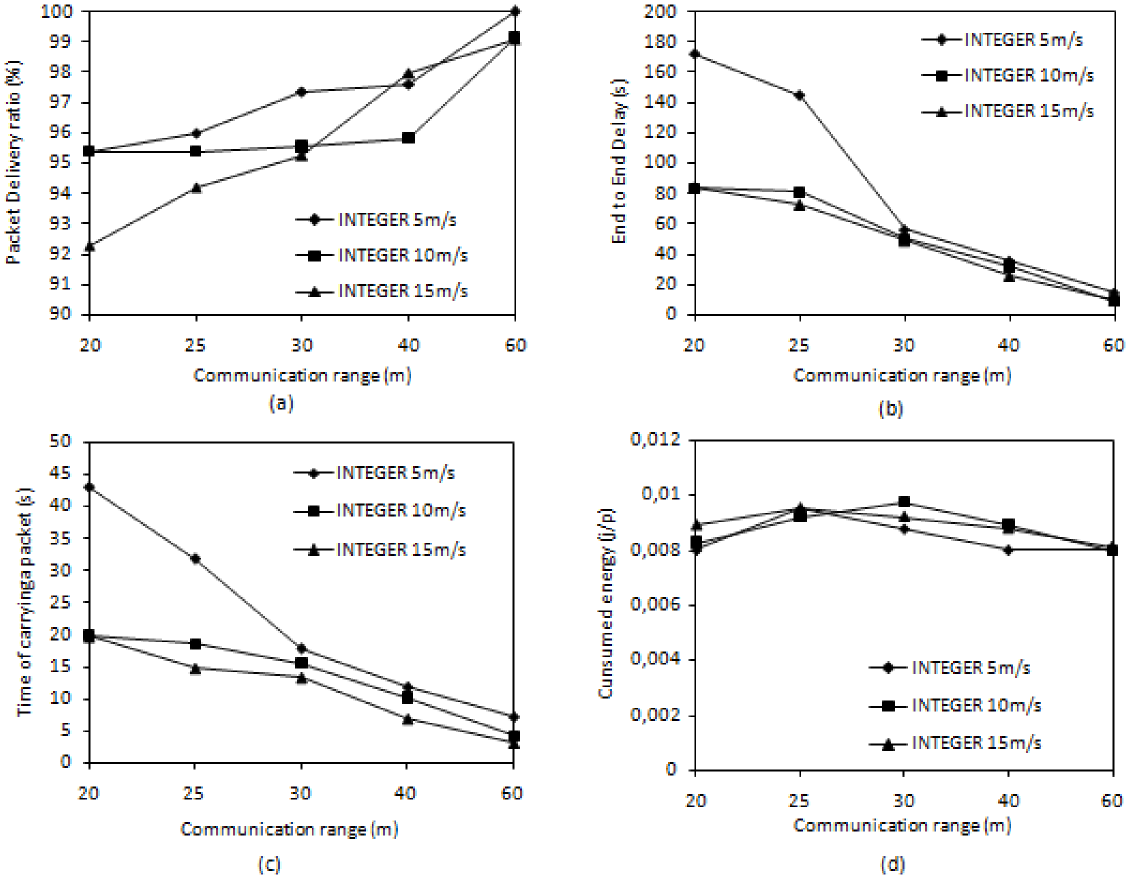


Figure 13: **a** Packet delivery ratio vs. node degree. **b** End-to-end delay vs. node degree. **c** Time of carrying a pcaket vs. node degree. **d** Consumed energy vs. node degree

In this test, we are more interested in studying the behavior of INTEGER when changing the mobility pattern. To do so, the maximum speed of nodes is varied from 5 to 15 m/s. In Figure 13 (a), when the speed of nodes is low (5m/s), this gives more link reliability, that is why the curve given by 5m/s outperforms those of 10m/s and 15m/s. Figure 13 (a) shows also that the delivery ratio increases with the increase of the communication range. This is because a packet holder has more candidates in its neighborhood. This same reason explains why the end-to-end delay in Figure 13 (b) decreases when increasing the communication range. In fact, more nodes become reachable within a single hop. This saves considerably the time for discovering neighbors and minimizes doing frequent hop-to-hop transmissions. Because it is obvious that with the increase of the communication range, the number of relay nodes participating in the routing process decreases, we chose to show in Figure 13 (c) how this influences also the time that a node is obliged to carry a packet before forwarding it to the next forwarder. With shorter communication range, a node has less candidate neighbors and the packet holder may not find easily a neighbor with better weight than itself, which obliges it to keep the packet for a long time until crossing a suitable forwarder. Add to that, if its speed is low, then the time for its displacement and the time to its neighborhood to change will be also long. This time will be reduced when a packet holder has a larger choice among its neighbors and the number of hops to reach the destination will be reduced, which saves the routing time. As for the consumed energy, Figure 13 (d) shows that the variation in smooth. This is mainly because the energy wasted in discovering frequently new neighbors is saved in case of larger communication range. A larger number of neighbors could be discovered at once but there is a need for more energy to transmit and receive *Position_Request* and *Position_Response* messages, also to transmit a packet if the selected neighbor is far from the sender, which makes such balance in the consumed energy. An interesting observation is that with the increase of communication range, all the curves tend to converge even when increasing the speed of nodes. This behavior is explained by the fact that from a packet holder perspective, when the communication range increases largely, whatever the speed of the sender, there will not be much change in its neighborhood since it can already reach much neighbors within a single hop.

4. INTEGER IN DELAY-TOLERANT NETWORKS

Intermittently connected Delay-Tolerant Wireless Sensor Networks (ICDT-WSNs) are a new branch of Wireless Sensor Networks, which combine both characteristics of Wireless Sensor Networks and Delay-Tolerant Networks (DTNs). Their main characteristics include short communication range, narrow bandwidth, limited energy and low computation capabilities in addition to the intermittent connectivity in which end-to-end paths between sources and destination do not always exist and if they do exist, most of the time are unstable and may break anytime during the routing process. Underwater WSNs, underground WSNs and Mobile WSNs –e.g. ZebraNet [135]- are well known examples of ICDT-WSNs. In our research, we are more interested in Mobile WSNs and their applications for monitoring individuals and animals. Thus, our focus will be devoted to Intermittently Connected Delay-Tolerant Mobile Sensor Networks (ICDT-MWSNs).

The challenges of ICDT-MWSNs can be divided into two classes:

- Link Challenges: Intermittent and unpredictable connectivity, low or variable delay, asymmetric data rates and high error rates, sudden disconnection and link loss due to mobility of nodes.
- Node Challenges: Mobility of nodes, limited power, low processing capability, minimal storage, short communication range and low bandwidth.

In the very recent survey about geographic routing in DTNs [70], Cao et al. observed a real research vacancy in terms of proposed geographic protocols for DTNs in the literature despite being a very promising communication way in such intermittent networks. Only seven up-to-date geographic protocols have been reviewed in the literature representing only 11% compared to numerous topological ones [136]. Motivated by this lack of attention by the research community and our conviction that our proposal INTEGER suits well delay-tolerant with intermittent connection scenarios, we propose to adapt INTEGER in the context of the delay-tolerant networks.

Cao et al. [70] identified several future directions that should be considered when designing geographic routing for ICDT-MWSNs that are already considered by INTEGER namely:

- *Handling the local maximum:* the local maximum problem happens when condition (21) is not fulfilled. In sparse networks, where opportunities to encounter adequate relay nodes are rare, this problem becomes more and more frequent resulting in drop of packets or long end-to-end delays. By adopting wisely the store-carry-forward strategy, INTEGER saves packets from being dropped by allowing the packet holder to keep the packet until finding a suitable relay.
- *QoS consideration:* knowing that frequent neighborhood discovery is energy costly and infrequent discovery may lead to missing many communication opportunities with neighbors that may be good candidates, INTEGER proposes an intelligent and mobility-based adaptive neighborhood discovery delay that maximizes the delivery ratio and minimizes the consumed energy.
- *Assistance of additional infrastructure:* In INTEGER, the mobile anchor that moves with dedicated path serves basically as location reference for mobile nodes but can also serve as a message ferry. In fact, if the mobile anchor is a neighbor of the packet holder and is going in the direction of the destination, it will be favored to be a relay since it has the fastest speed and its location error is negligible. It can also bridge the communication gap between disconnected nodes.
- *Combining MANET-based and DTN-based geographic routing:* This need comes from the variation of the network density in some application scenarios. In fact, when the network is dense, INTEGER applies the MANET communication mode by benefiting from more opportunities for the packet holder to choose the best forwarder among its numerous neighbors. In case of sparse network, INTEGER switches reactively to DTN mode by allowing the packet holder to keep the packet until meeting a suitable relay. Such intelligent switch allows reducing the packet end-to-end delay when being in MANET mode without the obligation to drop the packet when being in DTN mode.

Geographic routing protocols in DTNs have promising potential to be adopted by VANETs, UWSNs and ANs (Aeronautical Networks) scenarios because of their highly dynamic changes. Because INTEGER responds to major DTNs characteristics, we aspire and look ahead to apply INTEGER in such scenarios. To do so, we compare it with three other delay-tolerant geographic routing protocols, the very recent TBGR [93] with one copy mode, AeroRP [92, 137] with the Ferry mode and DD [138]. We associate the re-forwarding strategy in case of collisions to all protocols.

Since mobility of nodes is a significant challenge being one the main causes of intermittent connectivity, in the following tests, we vary the maximum speed of nodes to study its effect on the packet delivery ratio, the end-to-end delay and the local maximum occurrence per successfully delivered packet. Otherwise, the default values are applied.

Figure 14 clearly shows that INTEGER outperforms its delay-tolerant concurrent protocols in terms of delivery ratio, end-to-delay and even local maximum occurrence. Both TBGR and AeroRP consider the velocity of nodes in the relay selection. Accordingly, we strongly believe that the favorable performance of INTEGER is thanks to the consideration of the localization error in the selection of the relay node in addition to its refined selection by considering the reliability and the QoS factors.

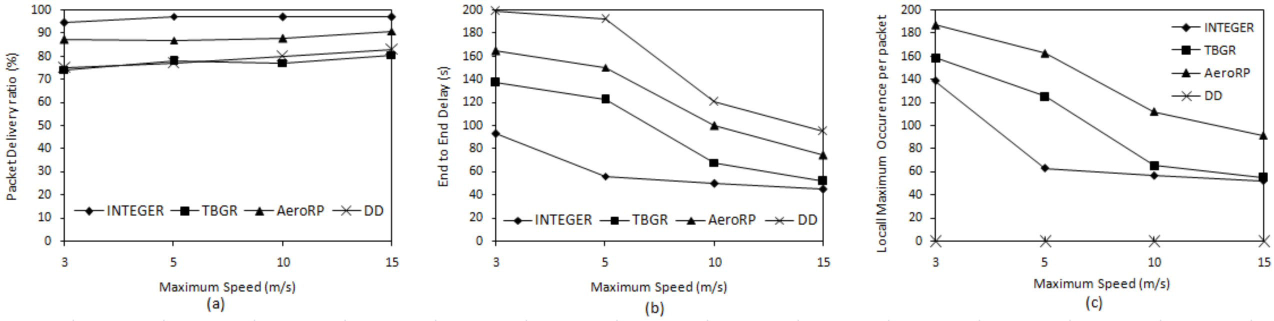


Figure 14: Comparison with delay-tolerant protocols

In terms of delivery ratio, Figure 14 (a) shows that when the maximum speed of nodes is moderate (5m/s), the gain in packet delivery with INTEGER is up to 21% compared with DD, up to 18% compared with TBGR, and up to 10% with AeroRP. With the same speed, Figure 14 (b) shows that INTEGER has the fastest latency, which is explained by Figure 14 (c) where the occurrence of local maximum problem is less for INTEGER than others. In this case, the time consumed while keeping the packet and discovering new neighborhood is saved by INTEGER.

The difference in the end-to-end delay between INTEGER and other protocols is important, up to 70% reduced compared to DD, 62% reduced compared to AeroRP and 54% reduced compared to TBGR. As for local maximum handling, INTEGER allows saving 60% and 55% compared to AeroRP and TBGR respectively as shown in Figure 14 (c) while DD does not deal with this problem, as there is only one transmission between the sources and destination.

CONCLUSION

In this chapter, we have proposed INTEGER, a novel geographic routing scheme intertwined with a localization algorithm especially designed for mobile wireless sensor networks. The scope of this scheme is its location error-resilience nature despite being typically geographic. In fact, INTEGER efficiently exploits the mobility of nodes and considers not only the geographic location of nodes but also their speeds and directions in addition to their location error bound to select the best forwarder. These crucial data are obtained by SDPL method that jointly localizes mobile nodes by estimating their positions through predicting their mobility pattern, that is, by predicting their speeds and their directions. To our knowledge, INTEGER is the first protocol that tackles localization and geographic routing for intermittently connected mobile sensor networks at the same time. The routing algorithm is composed of two main components namely the on-demand mobility-based adaptive neighborhood discovery and the best forwarder selection. The first consists on processing the discovery of neighbors by a node only if it has a packet to forward to save its energy and the energy of other nodes. To do so, a mobility-based adaptive time interval has been proposed to maximize the delivery of packets considering different network parameters. As for the best next forwarder selection, we have proposed a new approach that allows choosing the most adequate forwarder by considering the position, the speed, the direction, the link reliability, and the localization error of neighbors when making routing decisions. If no neighbor fits the requirements or if the packet holder is isolated, INTEGER adopts the carry-and-forward strategy that is, carrying the packet until finding a more suitable next forwarder. Thus, INTEGER could be well applied in delay-tolerant networks and intermittently connected networks. Simulation results have shown the efficiency of INTEGER and its resilience to localization error even when this latter is high thus could be used in applications where no exact positions can be obtained. It manages well the different speeds of mobile nodes from low speeds to high speeds thus could be applied in a large number of scenarios where the speed of nodes could vary or be very high such as monitoring wild animals. It also deals with networks with high traffic by keeping the highest delivery ratio thanks to the strategy of relay re-selection in case of collisions. The adopted strategy of carry and forward has proven its efficiency by giving chance to packet holders to keep the packet until finding other forwarders instead of dropping it. We further compared INTEGER with delay-tolerant protocols. Results showed that INTEGER outperforms its competitors by handling efficiently the local maximum problem while reducing the end-to-end delay and increasing the packet delivery.

Conclusions
And
Future Works

CONCLUSIONS

Mobile wireless sensor networks are recently gaining more interests due to their wide range of applications such as IoT applications, smart cities, healthcare, tracking, etc. The need to design efficient, scalable protocols for such networks makes it even harder for data forwarding and to get up-to-date locations, of either mobile sinks or mobile sensors. Furthermore, location errors are inevitable in real world scenarios and not considering those errors can lead to performance degradation. In this thesis, we have proposed a classification of the reviewed protocols according to mobility of nodes (sinks or sensors) and the localization error management.

Routing with mobile sinks has received much attention from the research community. However, most of proposed works focused only on how to keep nodes aware of the location of the moving sink. Nevertheless, other mobility patterns can also affect the performance of a geographic routing such as the number of sinks present in the network, the moving speed of sink, its trajectory and its presence or temporary absence from the network. To respond to such challenges, we have proposed M-Elastic routing protocol, an improved version of Elastic Routing [80], which considers different mobility patterns of the sinks. Results showed that the packet delivery ratio increases with the increase of the number of the mobile sinks present in the network. However, the high speeds of the sink can reduce the packet delivery ratio but can hasten the delivery delay by reducing the route length. Hence, in real-time scenarios, we propose to deploy multiple mobile sinks with high speeds. In M-Elastic, when the trajectory of the mobile sink is controllable, source nodes and intermediate nodes can predict the sink location at any time, which allow nodes to make smarter decisions about the selection of relay nodes. This impacts positively the packet delivery and reduces the packet end-to-end delay. However, the mobility of sink can cause its frequent disconnection from the network or absence during undefined time. M-Elastic considers this eventuality. Instead of dropping packets during the sink absence, thanks to its strategy by intelligently buffering and prioritizing important packets, M-Elastic saves up to 25% of packets from being dropped and important packets will be sent even after the fullness of the route.

Geographic routing relies also on the knowledge of neighbors' positions. Most of proposed geographic protocols assume that nodes are GPS-enabled. However, knowing that GPS can excessively drain sensors' batteries, GPS-free localization mechanisms can be good alternatives to keep unknown nodes continuously aware of their locations so to be able to communicate them when needed. For example, Anchor-assisted localization can be exploited for this purpose. Together with mobility prediction, we have proposed MA-SDPL (Multi-Anchors Speed and Direction Prediction-based Localization) and MH-SDPL (Multi-Hops Speed and Direction Prediction-based Localization), two localization algorithms that predict the speed and the direction of mobile nodes, to further predict their current locations. MA-SDPL considers the use of multiple mobile anchors (that can be the sinks themselves) to increase the chance for a node to receive more useful location beacons from different anchor positions, this will help in localizing unknown nodes quickly and to refine their estimations. MH-SDPL was proposed in case where the deployment of multiple anchors is not possible. The proposed method takes advantage of well localized nodes and makes them participate as secondary pseudo-anchors. To do so, nodes with more than 80% of location accuracy send in turn location beacons to their multi-hop neighbors to help them localize themselves. Geometric calculations are then applied by unknown nodes to estimate their positions. Performance evaluation showed that with MA-SDPL, the localization coverage is higher and unknown nodes calculate their estimations faster due to the rapid coverage of nodes by the multiple anchors which will reduce the localization error considerably. We have also tested MA-SDPL in a noisy environment. Obviously, when the noise is high or the noise source is nearer, this affects the localization error. As for MH-SDPL, the results showed that it reduces considerably the energy consumption compared to MA-SDPL thanks to its strategy of multi-hopping localization. These two methods can serve as a preliminary phase or can be executed conjunctly with any geographic routing for MWSNs.

Most of proposed geographic routing protocols assume that nodes are aware of their exact locations. However, this assumption is unrealistic in real world scenarios and location errors are inevitable. Mobility makes it even harder to know the accurate location due to frequent change and displacement of nodes. Not considering location errors in routing decisions has a direct impact on the degradation of the routing performance.

As a third contribution, we have proposed INTEGER (Intertwined Localization and Error-Resilient Geographic Routing), a novel geographic routing scheme intertwined with a localization algorithm especially designed for mobile wireless sensor networks. INTEGER considers the location errors when making routing decisions and exploits also the mobility patterns of nodes. Indeed, its best forwarder selection strategy considers not only distances to the sink but also the speeds of nodes and their directions, in addition to their location-error bounds. These data are provided by the localization method that is jointly executed with the geographic routing. SDPL (Speed and Direction Prediction-based Localization) is a GPS-free method that localizes continuously mobile nodes by estimating their positions. This estimation is based on mobility prediction of nodes' speeds and directions. The method provides also a location error bound that will be used in routing decisions to choose reliable relay nodes.

The routing mechanism is composed of two main components, an on-demand mobility adaptive neighborhood discovery and a best forwarder selection. The first consists on performing the neighborhood discovery by a node only if it has a packet to forward. This saves considerably the energy of nodes and their wireless resources. In addition, we have proposed a mobility-adaptive beaconing interval so to maximize data delivery while keeping the delivery delay reduced. Choosing a suitable time interval for neighborhood discovery is very important and can affect considerably the routing performance. In one hand, if this interval is too long, then many forwarding opportunities can be missed and the packet holder may miss good relay nodes that can forward the packet efficiently. In addition, the long beaconing interval may lead to long end-to-end delay. In the other hand, if this interval is too short, the packet holder may re-discover its previous neighbors since no much change happened. Besides, the frequent beaconing is energy draining and can increase the overhead and collisions due to excessive beacon exchanges. In light of this, we have proposed a function to calculate the adequate beaconing interval that considers the network parameters while keeping a trade-off between the energy consumption and data delivery.

As for the best forwarder selection, our strategy comes up with a new concept called "the packet direction". A packet direction number is assigned to each packet by the source so that only nodes going towards the sink and having the same direction as the packet direction will be candidates to forward the packet. The current packet holder assigns a weight to each of its neighbors where the quality of service (QoS) and the link reliability are considered in addition to the localization error. The QoS factor is expressed by an estimation of the delay of arrival of a packet to the destination while the link reliability factor is expressed considering the communication strength and the localization error of a candidate. The candidate with higher speed, stronger communication and less location error will be chosen as a relay node. If the packet holder has no neighbor or no neighbor fulfils the aforementioned requirements (local maximum situation), or the selected forwarder couldn't receive the packet (for example due to collisions), then the packet holder switches to DTN mode (Delay-tolerant mode), that it, carrying the packet while checking periodically for a better relay. This strategy of carry-and-forward while re-selecting a new forwarder helped in increasing the packet delivery ratio by up to 30% and allows INTEGER to be well applied in delay-tolerant and intermittently connected networks.

Simulation results showed the efficiency of INTEGER and its resilience to the localization error even when this latter is high which makes it suitable for a wide number of applications where accurate positions of nodes cannot be obtained. It deals well with different speeds of mobile nodes from low speeds to high speeds even without pause time. For example, the results show that when varying the speed of nodes, INTEGER improves the energy efficiency by 33%, increases the packet delivery ratio by 24% and reduces the number of relay nodes by 42% while maintaining a reduced delivery delay. Thus can be adopted in scenarios where nodes can have a wide range of speeds such as monitoring wild animals or monitoring vehicular traffic. INTEGER also works well with networks with high traffic by ensuring the highest delivery ratio compared to its concurrents thanks to the strategy of relay re-selection in case of collisions or failure of reception. We further tested INTEGER in delay-tolerant contexts. Results showed that INTEGER outperforms its competitors by handling efficiently the local maximum problem while reducing the end-to-end delay and increasing the packet delivery.

FUTURE RESEARCH PERSPECTIVES

Geographic routing investigations in mobile wireless sensor networks revealed that this type of forwarding requires further research and improvements under more realistic assumptions, mainly because of its promising benefits. The present work explores issues related to unrealistic assumptions which can influence the design and behavior of the routing protocols in real-life applications. Some of ongoing propositions and upcoming perspectives are summarized in the following:

- ***3D Localization and Routing using UAVs or Drones:*** While studying node distribution, localization and routing for MWSNs, the present work entirely focused on conventional 2D scenarios. Because the aim is to design practical localization and geographic routing algorithms, the proposed algorithms need to be evaluated in 3D scenarios. Although their behavior is assumed to be similar in 3D, it may bring forward sophisticated issues which have not been foreseen. Open research in 3D scenarios is motivated by the interest in WSN applications for space exploration, underwater surveillance, air and oceanic studies and the availability of new technologies such as UAVs [142]. Unconventional spaces require innovative solutions to answer more stringent needs for coverage and connectivity. Sometimes networks cannot benefit from high node density or devices with more resources, so intelligent routing protocols are needed to effectively cope with such issues, with obstacles and communication interferences. Several 3D geographic routing techniques have already been proposed in recent years [139-141], however, those propositions did not focus on localization inaccuracies having different approaches from those proposed in this thesis. Therefore, future work is needed in the extension of M-Elastic, SDPL and its variants and INTEGER for efficient localization and routing in 3D.
- ***Implementation of MA-SDPL and MH-SDPL with INTEGER:*** Initially, SDPL was proposed to be executed jointly with INTEGER to provide location information when needed by INTEGER. Knowing that in the case when multiple mobile anchors/sinks are available in the network and as seen in chapter 4, MA-SDPL has proven to more efficient in terms of high localization coverage and reduced localization error compared to SDPL. We are currently testing its efficiency when executed jointly with INTEGER. Earlier results are showing that the combination of multiple mobile anchors with the routing strategy of INTEGER allows to better choose relay nodes having less location errors but can generate a considerable number of collisions due to the number of beacons from the anchors helping in localizing nodes and beacons from relay nodes to perform neighborhood discovery. A study is in progress about intelligently introducing a lag between these two kind of beacons to reduce collisions thus to reduce the relay re-selection and packet re-forwarding.

  Comparatively with basic SDPL, MH-SDPL reduces considerably the localization error thus if implemented with INTEGER, it can improve the performance of INTEGER in choosing efficiently relay nodes.
- ***An On-Demand Mobility Prediction-based dynamic neighborhood discovery:*** A key component of INTEGER is its on-demand adaptive neighborhood discovery where a function has been proposed to calculate the beaconing interval that considers the network parameters and general mobility patterns. The proposed strategy allows having an adequate and average interval for all nodes that keeps a trade-off between the energy consumption and the data delivery. However, this interval is static and may not be suitable for all nodes, for example nodes moving with very high speeds or nodes that move with very slow pace. We are currently in the process of elaborating a new function that provides dynamically each node with its suitable beaconing time interval based on its predicted speed, which makes this new interval more realistic.

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