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**ROUTING PROTOCOL OPTIMIZATION IN CHALLENGED MULTIHOP
WIRELESS NETWORKS**

**OPTIMISATION DES PROTOCOLES DE ROUTAGE DANS LES RÉSEAUX
MULTI-SAUTS SANS FIL À CONTRAINTES.**

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Abstract

Great research efforts have been carried out in the field of challenged multihop wireless networks (MWNs). Thanks to the evolution of the Micro-Electro-Mechanical Systems (MEMS) technology and nanotechnologies, multihop wireless networks have been the solution of choice for a plethora of problems. The main advantage of these networks is their low manufacturing cost that permits one-time application lifecycle. However, if nodes are low-costly to produce, they are also less capable in terms of radio range, bandwidth, processing power, memory, energy, etc.

Thus, applications need to be carefully designed and especially the routing task because radio communication is the most energy-consuming functionality and energy is the main issue for challenged multihop wireless networks.

The aim of this thesis is to analyse the different challenges that govern the design of challenged multihop wireless networks such as applications challenges in terms of quality of service (QoS), fault-tolerance, data delivery model, etc., but also networking challenges in terms of dynamic network topology, topology voids, etc. Our contributions in this thesis focus on the optimization of routing under different application requirements and network constraints. First, we propose an online multipath routing protocol for QoS-based applications using wireless multimedia sensor networks. The proposed protocol relies on the construction of multiple paths while transmitting data packets to their destination, i.e. without prior topology discovery and path establishment. This protocol achieves parallel transmissions and enhances the end-to-end transmission by maximizing path bandwidth and minimizing the delays, and thus meets the requirements of QoS-based applications. Second, we tackle the problem of routing in mobile delay-tolerant networks by studying the intermittent connectivity of nodes and deriving a contact model in order to forecast future nodes' contacts. Based upon this contact model, we propose a routing protocol that makes use of nodes' locations, nodes' trajectories, and inter-node contact prediction in order to perform forwarding decisions. The proposed routing protocol achieves low end-to-end delays while using efficiently constrained nodes' resources in terms of memory (packet queue occupancy) and processing power (forecasting algorithm). Finally, we present a topology control mechanism along a packet forwarding algorithm for event-driven applications using stationary wireless sensor networks. Topology control is achieved by using a distributed duty-cycle scheduling algorithm. Algorithm parameters can be tuned according to the desired node's awake neighbourhood size. The proposed topology control mechanism ensures trade-off between event-reporting delay and energy consumption.

Key-words: WSN, WMSN, DTN, MDTN, Routing, Multipath, Energy-Aware, Contact Forecasting, Geocast, Trajectory-Assistance, Topology Control, Duty-cycle scheduling.

Résumé

Durant ces dernières années, de nombreux travaux de recherches ont été menés dans le domaine des réseaux multi-sauts sans fil à contraintes (MWNs: Multihop Wireless Networks). Grâce à l'évolution de la technologie des systèmes micro-electro-mécaniques (MEMS) et, depuis peu, les nanotechnologies, les MWNs sont une solution de choix pour une variété de problèmes. Le principal avantage de ces réseaux est leur faible coût de production qui permet de développer des applications ayant un unique cycle de vie. Cependant, si le coût de fabrication des nœuds constituant ce type de réseaux est assez faible, ces nœuds sont aussi limités en capacité en termes de: rayon de transmission radio, bande passante, puissance de calcul, mémoire, énergie, etc. Ainsi, les applications qui visent l'utilisation des MWNs doivent être conçues avec une grande précaution, et plus spécialement la conception de la fonction de routage, vu que les communications radio constituent la tâche la plus consommatrice d'énergie.

Le but de cette thèse est d'analyser les différents défis et contraintes qui régissent la conception d'applications utilisant les MWNs. Ces contraintes se répartissent tout le long de la pile protocolaire. On trouve au niveau application des contraintes comme: la qualité de service, la tolérance aux pannes, le modèle de livraison de données au niveau application, etc. Au niveau réseau, on peut citer les problèmes de la dynamique de la topologie réseau, la présence de trous, la mobilité, etc. Nos contributions dans cette thèse sont centrées sur l'optimisation de la fonction de routage en considérant les besoins de l'application et les contraintes du réseau.

Premièrement, nous avons proposé un protocole de routage multi-chemin "en ligne" pour les applications orientées QoS utilisant des réseaux de capteurs multimédia. Ce protocole repose sur la construction de multiples chemins durant la transmission des paquets vers leur destination, c'est-à-dire sans découverte et construction des routes préalables. En permettant des transmissions parallèles, ce protocole améliore la transmission de bout-en-bout en maximisant la bande passante du chemin agrégé et en minimisant les délais. Ainsi, il permet de répondre aux exigences des applications orientées QoS.

Deuxièmement, nous avons traité le problème du routage dans les réseaux mobiles tolérants aux délais. Nous avons commencé par étudier la connectivité intermittente entre les différents et nous avons extrait un modèle pour les contacts dans le but pouvoir prédire les futurs contacts entre les nœuds. En se basant sur ce modèle, nous avons proposé un protocole de routage, qui met à profit la position géographique des nœuds, leurs trajectoires, et la prédiction des futurs contacts dans le but d'améliorer les décisions de routage. Le protocole proposé permet la réduction des délais

de bout-en-bout tout en utilisant d'une manière efficace les ressources limitées des nœuds que ce soit en termes de mémoire (pour le stockage des messages dans les files d'attente) ou la puissance de calcul (pour l'exécution de l'algorithme de prédiction).

Finalement, nous avons proposé un mécanisme de contrôle de la topologie avec un algorithme de routage des paquets pour les applications orientées évènement et qui utilisent des réseaux de capteurs sans fil statiques. Le contrôle de la topologie est réalisé à travers l'utilisation d'un algorithme distribué pour l'ordonnancement du cycle de service (*sleep/awake*). Les paramètres de l'algorithme proposé peuvent être réglés et ajustés en fonction de la taille du voisinage actif désiré (le nombre moyen de voisin actifs pour chaque nœud). Le mécanisme proposé assure un compromis entre le délai pour la notification d'un évènement et la consommation d'énergie globale dans le réseau.

Mots-clés: réseaux de capteurs sans fil, réseaux de capteurs multimédia, réseaux tolérants aux délais, réseaux mobiles, routage, routage multi-chemin, conservation d'énergie, prédiction des contacts, routage géographique, contrôle de la topologie, ordonnancement de l'activité du nœud.

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In memory of my dear father,

To my dear mother, brother and sister,

To my uncle Boualem who was always there for every important decision of my life.

To my fiancée Fatima and all my family,

I dedicate this work,

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Chapter 1

1 Introduction

1.1 Context and Motivation

Great research efforts have been carried out in the field of low-cost multihop wireless networks (MWNs), especially wireless sensor networks (WSNs). Thanks to the evolution of the Micro-Electro-Mechanical Systems (MEMS) technology and nanotechnologies, these challenged networks have been the solution of choice for a plethora of problems.

The main advantage of these networks is their relative low manufacturing cost. Thanks to this advantage, applications developers could offer the comfort of one-time application lifecycle. Indeed, such networks' nodes can be dropped and left working on batteries without worrying to replace their batteries or even retrieving them from the deployment field. However, the other side of the coin is that if the network nodes are low-costly to produce, they are also less capable in terms of radio transmission range, bandwidth capacity, processing power, memory storage, etc. Due to these limitations, applications that use low cost MWNs need to be carefully designed and classic approaches that are valid for today's networks (i.e. AdHoc Networks) do not apply for these networks. Every transmitted bit of data, every executed processor instruction, and every stored byte need to be totally justified and necessary.

Many research works can be found in the literature where researchers have used challenged multihop wireless networks for various applications (natural phenomenon monitoring, data gathering and dissemination, etc.). Most of these research works did not consider the minimal capabilities of these networks as a stringent constraint. Such inefficiency can be witnessed through routing protocols based on massive data packet exchange for topology discovery or path construction. These protocols have been inherited from the advances achieved in the field of ad-hoc wireless networks. Another inefficiency can also be noticed when it comes to some algorithms run on the wireless nodes. A large number of research works developed CPU-demanding data processing algorithms, thus, the carried energy will deplete quickly. Therefore, this comes in contradiction with the philosophy behind low cost multihop wireless networks.

This thesis was undertaken with the strong belief that challenged MWNs are not costly to manufacture but they are very limited. Thus, solutions that can be proposed must be as optimized as possible to be in line with the idea that low cost MWNs can be used to achieve an acceptable

service as good as what legacy infrastructures can achieve and without making the wireless nodes more expensive to produce by putting more energy, enhanced radio communications hardware, powerful CPUs, or any additional hardware (i.e., mobility components).

1.2 Research Problem

The works that have been carried out in this thesis are oriented to the multihop wireless networks (MWNs) in general but especially to the most challenged networks among them including wireless sensor networks (WNSs), wireless multimedia sensor networks (WMSNs), and mobile delay-tolerant networks (MDTNs). In order to present a clear scope of the work, we introduce the challenges that are related to our studied subject.

Low-cost multihop wireless networks are composed of a large number of nodes which are small in size. These nodes are capable of sensing data from the deployment environments, processing the data and communicating the results to the end user or the control entity. They can also communicate with each other and cooperate in order to achieve a determined task. In addition to the inherited characteristics related to wireless communications, low cost multihop wireless networks have other characteristics inherent to the way they operate:

- *Limited capabilities.* Nodes often operate on (irreplaceable) batteries with: limited energy, transmit power, memory and computing capabilities.
- *Short range radio communications.* Network nodes use multihop communications in order to transmit data for long distances.
- *Dynamic network topology.* Network topology may be subject to frequent changes due to nodes' failure, nodes' mobility or any energy conservation mechanism run by the node to adjust the transmitting power or to schedule the node activity (wakeup/sleep scheduling).
- *Data centric communications model.* Collected data are more important than the source nodes identities (unless the node identifier actually carries some information such as the location where the data has been measured which is the case when geographical node addressing is used).
- *Dense and redundant node deployment.* In order to leverage nodes' failures and to increase the overall network lifetime, nodes are often deployed densely and redundantly.
- *Need for self-* functionalities (organization, control, healing, etc.).* Since wireless nodes are often left unattended, such functionalities need to be taken into consideration during the design steps of the applications.

Low cost MWNs have been used for various applications in different fields: military and defence (border monitoring, intrusion detection, video surveillance, etc.), civil (infrastructure health monitoring), natural environments (forest fire, volcano activity, oceanography, etc.), commerce (indoor localization, precision farming, traffic control, etc.), medical (disaster prevention, medical care, etc.). It is easy to notice that these applications have different needs in terms of transmitted data volumes, data rates, reporting frequencies, etc. Some of these applications require the transmission of large quantities of data (especially when it comes to multimedia contents such as video, audio, or even a basic image stream). Sending such data streams through low cost MWNs may be very difficult, even impossible in certain situations. The main difficulty is due to the low bandwidth available in each hop. To overcome this problem, the use of multiple path transmission seems of good choice. However, the construction of multiple paths for parallel transmission identifies some challenges such as network topology awareness, path building and maintenance, and finally load-balancing. Since such applications put a heavy load on actual data transmission, overburdening these data communications with control packets is inefficient as done by the huge majority of research works in the field of multipath routing protocols for wireless sensor networks. Thus, an interesting challenge in such configuration is an online multipath routing protocol; a routing protocol where the establishment, maintenance and load-balancing of multiple parallel paths is achieved without a complete knowledge of the network topology.

In other applications where nodes are densely deployed across the sensing field but the collected data is not frequent and not bandwidth demanding (such as intrusion detection or environment monitoring applications), the data communications are event-driven. In this case, it is interesting to not use the entire network nodes to achieve such service. It is customary to put the maximum number of wireless nodes in a low consuming energy state (a sleep state) without degrading the desired service in order to achieve energy efficiency and thus maximizing the network lifetime. Such solutions will result in a dynamic network topology due to nodes' wakeup/sleep states switching. Therefore, the challenge is to design wakeup/sleep scheduling algorithm that maintains a routing infrastructure capable of routing data packets from any source towards the destination. Along this scheduling algorithm, and to reiterate our vision on low cost MWNs, network topology awareness, construction and maintenance do not need to be energy, memory or power consuming.

In a more advanced scenario, certain application can make use of mobile wireless nodes. If the interest area becomes larger, nodes may be disconnected from each other for a long period of time resulting in intermittent connectivity between network nodes and thus, a highly dynamic network topology. Such infrastructure is useless for a majority of applications unless those that

tolerate relatively large end-to-end delays due to the store-carry-and-forward mechanism used to forward data packets from the source to the destination. In this context, the efficiency of the routing protocol depends heavily on the amount of knowledge the mobile node can acquire before performing its routing decisions. The challenge behind the design of an efficient routing protocol for mobile multihop wireless networks is first, the guarantee for a source to reach the destination, and second, the minimization of the end-to-end delay. There are other secondary challenges such as the resources utilization. Indeed, some routing protocols propose to duplicate the data packets (replication-based protocols) in order to increase the probability of meeting the destination node earlier. These protocols excessively fill intermediate nodes' queues with duplicated data packets which will lead to inefficient resource utilization. In order to overcome this challenge, any other knowledge about the network topology becomes beneficial and can enhance the routing protocol. Examples of additional knowledge include:

- The use of geographical addresses permits the nodes to determine the trajectory of a node during a contact. Thus, this information can help to make a decision about whether to forward the packet to this node or not.
- The analysis of the inter-nodes encounters history can ease the forecast of the next contact. More information can be forecasted too, such as next contact date, next contact duration, etc.

Other challenges can be found in every specific application. However, the enumeration of all the possible challenges is out of the scope of this thesis.

1.3 Contributions

During this thesis, we focused on some routing challenges for Multihop Wireless Networks. In this scope, the main goal of this thesis is to study different routing issues and to propose adequate solutions. Towards this goal, the problem of QoS-based applications over wireless sensor networks has been treated by the proposition of an online multipath routing protocol. The problem of intermittent connectivity and end-to-end delay minimization in the case of mobile delay-tolerant networks has been tackled by the proposition of a model of inter-node contact forecasting and forwarding-based routing protocol (i.e. only a single copy of the data packet exists in the entire network). Finally, we have addressed the problem of the changing topology resulting from wakeup/sleep scheduling (mechanism that aims to minimize the energy consumption) by the proposition of a scheduling algorithm along topology control mechanisms.

The main contributions of this thesis can be summarized as follows:

- *Online multipath routing protocol for WMSNs*: our first contribution targeted QoS-based applications such as real-time applications using densely deployed wireless multimedia sensor networks, where nodes are equipped with audio / visual sensors. Such applications generate high volumes of data that need to be transmitted across low capacity links in a hop-by-hop basis. In order to not drain the nodes energy quickly, our proposed routing protocol relies on geographical node addressing and greedy packet forwarding in order to establish multiple paths without the knowledge of the entire network topology (only one-hop neighbourhood awareness is used). Unlike *offline* multipath protocols where paths building phase precedes data transmission phase, our routing protocol establishes multiple paths during the data transmission, i.e. as data packets advance from the source to the destination, they are forwarded across different paths. These multiple paths allow parallel transmissions, and thus, achieve lower end-to-end delays and load-balancing since the heavy load of high volumes of data transmissions becomes spread over a large number of nodes contrary to single-path routing protocols.
- *Inter-node contact model & Forwarding-based routing protocol for MDTNs*: Our second contribution focused on routing in delay tolerant networks and especially mobile DTNs. In such networks, nodes exhibit intermittent connectivity resulting in a highly dynamic network topology. We have considered a city-wide mobile network composed of different nodes regarding their mobility model: (1) regular nodes represented by the mobility of buses or trams through the use of defined time schedules and routes, (2) irregular nodes represented by the mobility of users' cars, taxis, etc. having random routes and schedules, and (3) static nodes represented by hotspots across the city. Initially, we have studied the inter-node behaviour in this context and derived an inter-node contact model that is based upon time series analysis. In a secondary step, we proposed a routing protocol that makes use of the derived contact model for forecasting next inter-node encounters, but it also makes use of knowledge about nodes locations and trajectories in order to perform routing decisions. We have showed that our routing protocol does not require either intensive computation for contact forecasting or important memory space for packets buffering in order to achieve the minimization of the end-to-end delays.
- *Wakeup/Sleep scheduling algorithm & Topology control mechanisms for WSNs*: our third contribution focused on energy efficient routing infrastructure for dense WSNs used for event-driven applications. We have proposed a distributed wakeup/sleep scheduling algorithm that can be tuned in order to prune the active neighbourhood to a desired average neighbourhood size. This restricted active neighbourhood permits the

economization of nodes' energy by letting various nodes to enter a low energy-consuming state (sleep state) without degrading the data forwarding process. We have also proposed additional mechanisms for routing path establishment and maintenance in order to route data packets efficiently.

1.4 Thesis Structure

This thesis is organised as follows:

Chapter 2: reviews the challenges and considerations that govern routing protocols for multihop wireless networks with a certain focus on the end-applications requirements and the different issues that these applications face at different levels of the communications stack. It gives a brief overview of the targeted applications and presents a classification of the different issues and challenges tackled by existing routing protocols. An overview of routing protocols for WSNs is presented. This chapter also discusses the problem of routing in DTNs by introducing these networks, their characteristics, and a brief overview and classification of existing routing protocols for DTNs. Finally, techniques for multihop wireless networks self-organization are also discussed.

Chapter 3: presents the details of our first contribution: an online multipath routing protocol for wireless multimedia sensor networks for a QoS-based application. We first review some routing protocols that influenced the design of our routing protocol such as geographical routing protocols but also offline multipath protocols for WMSN. Then, we describe our routing protocol components: neighbour selection, packet forwarding scheme, load balancing, and topology holes avoidance. The proposed solution takes into account both residual energy and packets transmission delay in order to perform routing decisions.

Chapter 4: presents the details of our second contribution namely ORION, a routing protocol that is suitable for data dissemination applications with less stringent delay constraints and for use in mobile multihop wireless networks with intermittent connectivity. We first study the inter-node contact behaviour and derive an inter-node contact model based on time series analysis. Then, we present the details of ORION routing protocol by explaining the contact forecasting process as well as the forwarding algorithm. In this contribution, a focus is given to resource efficiency either in forecasting algorithm or queue occupancy for the store-and-carry-forward mechanism.

Chapter 5: presents our third contribution; a stochastic topology control mechanism based on wakeup/sleep states scheduling. For monitoring applications based on a static and dense multihop wireless networks, keeping all the nodes active in the same time is not energy efficient.

First, and according to certain wakeup/sleep statistical distribution, we show that the best statistical distribution parameters can be computed to meet certain requirements in terms of node's neighbourhood size. After the estimation of these parameters, we propose distributed scheduling algorithm that keeps a minimal topology working for achieving energy efficiency without degrading the data delivery process both in terms of end-to-end delays and resource utilization.

Chapter 6: summarizes our contributions, and concludes this thesis. Future perspectives and improvements to our contributions are also discussed.

Chapter 2

2 Challenged Multihop Wireless Networks

The recent advances in Micro-Electro-Mechanical Systems (MEMS) technologies [1] have unlocked a wide range of potential applications [2] that make use of multihop wireless networks.

These networks are likely to be composed of hundred, and potentially thousands of small wireless nodes powered on batteries, functioning autonomously, and often without access to a renewable energy source. These nodes have the ability to sense the physical environment, process the obtained information and communicate using short radio interfaces. Many applications deployment fit to have a specific node called "sink node" which is responsible for collecting and processing the information received from the other nodes.

Energy is considered as the main issue of these wireless networks. Indeed, such networks are often considered for hostile environments, but also wide and wild areas in order to ensure specific applications. Such applications include battlefield surveillance, volcano activity monitoring, wild animals tracking, etc. Therefore, it is difficult to replace or recharge the battery. Thus, these applications are deployed for just one lifecycle. Energy consumption has then to be reduced in order to maximize the application lifetime and delay another deployment. Radio communication is considered as the most energy consuming functionality. Since nodes cannot transmit data packets over long distance to avoid draining energy, transmit power is adjusted to its minimum allowing short range communications. This reality has led to a new communication paradigm: *multihop communications*. In order to communicate data over long distances, wireless nodes act as relays for other nodes in order to forward packets from their source towards the destination in a hop-by-hop basis. Figure 1 represents an example of such networks.

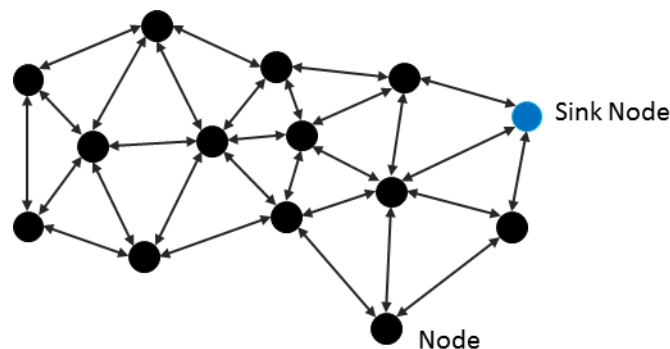


Figure 1: Multihop Wireless Network Architecture

Furthermore, using a single path may quickly deplete the residual energy of individual nodes across this path. This will result in unbalanced energy consumption across the sensing field, and hence negatively affects the overall network lifetime.

Finding and establishing a routing path across the network may be very challenging if the network topology has to become dynamic. Network topology is dynamic when using mobile wireless nodes, but also in static networks where nodes adopt a wakeup/sleep scheduling in order to reduce energy consumption, or simply due to nodes failure. In this context, the problem of finding a routing path from the source to the destination evolves to a more challenging problem: of finding a routing path in a changing topology in time.

Wireless node resources such as computing and memory capabilities are also an important issue. Indeed, if these networks benefit from low manufacturing costs, they suffer from minimal capabilities: less powerful CPUs, small memory size, etc. This fact makes complex algorithms impossible to be implemented in such nodes, but advocates the design and implementation of simple but efficient algorithms for all the functionalities: data gathering, data processing, packet routing, topology control, etc.

Due to the characteristics of low cost and easy deployment of these networks, they have attracted more and more attention and have been used in many different applications: Wireless Sensor Networks (WSNs) [3][4][5], Wireless Multimedia Sensor Networks (WMSNs) [6], Wireless Sensor and Actuator Networks (WSANs) [7], Wireless Mesh Networks (WMNs) [2], Underwater Acoustic Sensor Networks (UASNs) [8], Mobile Wireless Sensor Networks (MWSNs) [9], Delay-Tolerant Mobile Networks (DTMNs) [10], Unmanned Aerial Vehicles (UAVs) [11], etc.

2.1 Potential Applications Overview

Low cost wireless multihop networks, and especially WSNs, have been used for a variety of applications such as military surveillance [11], environment monitoring [13], structural health monitoring [14], asset tracking [15], domestic networks and home automation [16], smart places [17], industrial process control [18], medical care [19], etc. According to [20], applications can be categorized based on the data interaction patterns:

- *Event-Detection*: wireless nodes stay in a sensing state, and once they have detected a certain event, they report this information the sink node. Sensing can be done locally and continuously, but reporting can be triggered if certain rules apply such as a measured value that exceeded a determined threshold. Some event-driven applications may require the cooperation of a group of nodes in order to decide whether an event has occurred or no.

- *Periodic Sampling*: in such applications, nodes sense periodically the physical environment and report the measurement to the sink node. Measurement can be triggered by the application on a detected event (e.g. activating audio capture in a video surveillance application when an intrusion has been detected). Another application based on periodic measurement can be air pollution monitoring [21].
- *Target Tracking*: an event can be dynamic in time and space such as an intruder in the case of surveillance applications. Wireless nodes can be used to measure and report to the sink target information such as location, speed, direction, etc. Nodes have to cooperate between them in order to consolidate an efficient report to be sent to the sink node.
- *Actuators Control*: since wireless nodes embed different types of hardware along the physical sensors, such nodes can also be used in applications where an action can be needed as a response to a certain detected event. In this case, the node is not only part of the identification process but it is part of the response process too. WSN-based applications fall into this category.

2.2 Wireless Node Architecture

Before describing the high level challenges that affect the multihop wireless networks, we describe the node-level architecture for future references. Figure 2 represents a typical wireless node with sensing capabilities:

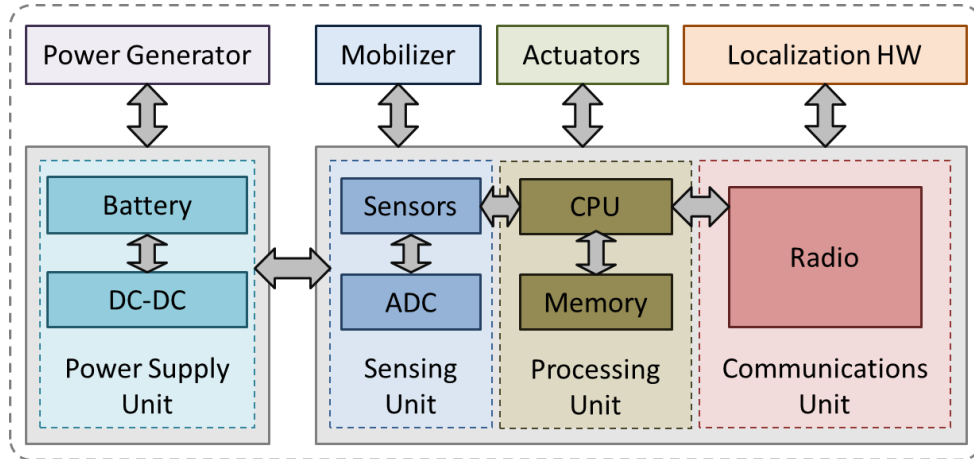


Figure 2: Wireless Node Architecture

A wireless node consists of the following elements, some are essential whereas other components may be optional:

- *Sensing Unit*, which includes one or several sensors along analog-to-digital (ADC) converters (if necessary) for data collection.

- *Processing Unit*, which includes a microprocessor and memory in order to run any processing code.
- *Communications Unit*, which includes a radio transmitter/receiver for wireless communications.
- *Power Supply Unit*, which includes one or more batteries.
- *Localization Hardware*, any hardware that provisions the node with location information such as GPS.
- *Actuators*: any hardware that is part of the application control system.
- *Mobilizer*: a hardware that allows the wireless node to move to another location (motors, wheels, wings, ...)
- *Power Generator*: any component to permit the recharging of the batteries or to be used as primary energy source (solar panel, dynamo, ...)

2.3 Low Cost Multihop Wireless Networks Characteristics

Unlike other wireless networks, such as ad-hoc networks, challenged multihop wireless networks have the following characteristics:

- *Application-specific*. Low cost-multihop networks have gained a lot of attention and are widely used for various applications as presented earlier. However, for different applications, there are different needs and requirements. This fact has led to the apparition of multiple network architectures and protocols.
- *Easy deployment*. Thanks to the distributed algorithms that allow an autonomous behavior, these networks do not need any infrastructure establishment in advance. In some applications, wireless nodes can be dropped for the air.
- *Scalability*. Due to the low manufacturing cost, these networks can be composed of hundreds or thousands of nodes. Thus, deploying such networks allows the coverage of wide areas.
- *Changing Topology*. Due to nodes' characteristics, connectivity may be highly dynamic due to various reasons: mobility, short radio range, or nodes' failure. Network topology dynamicity can also results from the deployment of new nodes in the same sensing field.
- *Unattended Functioning*. Such networks can be deployed in areas without the need for a human attending such as hostile and dangerous environments (e.g. battlefield, volcano, etc.). Thus, these networks must be self-organizing i.e. nodes organize themselves automatically after deployment. Self-management and self-healing functionalities are also required in order to deal with any network topology changes.

- *Converged Traffic*. Many applications based on such low-cost multihop wireless networks rely on the presence of a special node (the sink node) which collects the data from the other nodes. Multiple sink nodes may exist according to the application requirements. The role of such node is the collection of the data but also the processing and the generation of reports that describe the application functioning.

2.4 Challenges and Design Principles

The main factors that drive the architecture design of low cost multihop wireless networks and especially WSNs [6] are:

- Fault-Tolerance,
- Scalability,
- Manufacturing cost,
- Hardware constraints,
- Physical environment,
- Network topology,
- Energy consumption.

These challenges are describes in the following sub-sections:

2.4.1 Fault-Tolerance

Fault -tolerance [22][23] is the ability to maintain the network functioning in the presence of faults. The network reliability is affected by different faults due to different reasons such as node's failure, energy depletion, bad deployment, etc. the failure of a single or a set of nodes should not affect the overall functioning of the network. It is worth to notice that architecture and protocols for these networks may be designed to address a predetermined level of fault-tolerance as perfect fault-tolerance may be very difficult to achieve. This level may depend on the end-application. For example, an application for weather monitoring may have a lesser fault-tolerance level than the level for a battlefield surveillance application.

2.4.2 Scalability

Challenged multihop wireless networks may be composed of hundreds or, potentially, thousands of nodes. This number may reach the extreme value of a million for some applications. Designed algorithms and protocols must be capable of handling such number of nodes [24]. The high density of these nodes within the sensing field must be considered too as it affects greatly most of the nodes tasks (radio transmission, packet routing).

2.4.3 Manufacturing Cost

If the network is composed of a large number of nodes, the cost of a single node is very critical as it affects the cost of the overall network [25]. If this cost is more expensive than the cost of deploying traditional networks, then the use of this network is not cost-justified. Thus, the cost of single node must be kept very low. Moreover, as nodes may embed other units, the cost of a single node may become very challenging as it will consist of finding the best tradeoff between the capabilities that may equip the wireless node and its total cost.

2.4.4 Hardware Constraints

The main hardware constraint is the size of the node [26] since all the utilized units must fit into a small size module. Other constraints may be added such as the low energy consumption and the resistance to extreme environment conditions (humidity, temperature, pressure, etc.). Overall, since the network may be deployed for only one lifetime, the node hardware must resist and last as long as possible.

2.4.5 Physical Environment

Nodes are often deployed within or very close to the studied phenomenon. Moreover, some environments may be hazardous for human attendance. Thus, these challenged networks must work unattended. Such environments include: biologically contaminated field [27], battlefield, under water, volcanos, etc.

2.4.6 Network Topology

Deploying a large number of nodes requires efficient algorithms for topology maintenance [28]. This topology maintenance can be composed of three stages: (1) deployment, (2) post-deployment, and (3) redeployment. For deployment, nodes can be dropped in mass or placed one by one in the sensing field. After deployment, changes to the topology must be handled. These changes include node failure due to energy depletion or node destruction, nodes mobility, etc. Finally, if the network topology cannot recover from severe topology changes such as complete partitioning, redeployment of new nodes may be necessary. These new nodes must then be placed efficiently in order to recover the network topology from its partitioning.

2.4.7 Energy Consumption

Due to their small size, nodes are very limited in energy [29]. For some applications, replacement or recharging of batteries is impossible. Since the node lifetime depends on the battery lifetime, algorithms and protocols designed for these challenged networks must be energy-aware. In some applications, where energy is not an issue (nodes placed in vehicles), the focus is on the

application requirements, such as quality of service (QoS), or resource efficiency in order to achieve the desired application tasks with less powerful CPU and less memory.

2.5 Challenges across the Communication Protocols Stack

In this sub-section we present different challenges that researchers are facing at different levels of the communications stack.

2.5.1 Applications Level Challenges

Applications challenges may include: quality of service, bandwidth, and data delivery model.

2.5.1.1 *Quality of Service*

In some applications, data must be delivered to the destination within a certain period of time from the moment it has been sensed; otherwise the data will be useless. Therefore, end-to-end delays should be bounded for time-constrained applications. However, in many applications, conservation of energy, which directly impacts the network lifetime, is considered relatively more important than the quality of the service. Hence, the design of time-constrained application using low cost multihop wireless networks is based on a trade-off between the quality of service, and the energy consumption.

2.5.1.2 *Bandwidth*

Some applications may require the sensing, the processing and the transmission of high volumes of data as it is the case for multimedia applications. These applications face the problem of limited link bandwidth. For example, it may be impossible to send a multimedia stream across a single path in a hop by hop basis and to meet the delay constraints. To overcome this problem, researchers propose the use of cooperative sensing where a group of nodes cooperate in order to send partial information that is later reconstructed at the sink node. Another solution consists of multiple path transmission, where the source node sends the sensed data across parallel disjoint paths in order to boost the end-to-end transmission.

2.5.1.3 *Data Delivery*

Applications may have different requirements in terms of data delivery model [30].

- *Periodic (or Time-driven)*. In this category, each node periodically sends data samples to the destination node. Most monitoring applications rely on this data delivery model.
- *Event-driven*. In this category, nodes send data to the destination node once they detect an event. Event-detection can be very simple such as monitoring a measured value until it reaches a predetermined threshold, then a report is sent to the sink node. In some

applications, event-detection can be very complex such as in intrusion-detection applications, where nodes cooperate among them in order to avoid the detection of false positives, before reporting the event to the sink node.

- *Query-driven*. In this category, nodes send packets to the sink when they receive a query packet from a control entity. For example, in medical care applications, the doctor may query the data of one or some of his remote patients equipped with body wireless sensor network.
- *Hybrid*. In this category, one or more of the previous data delivery models are used simultaneously. For example, nodes can trigger a report to the sink upon the detection of a certain event and periodic samples follow after for a certain period of time [31].

The data flow type impacts directly the application. For periodic data flows, compression or in-network aggregation may be of good choice, in order to reduce the data packets that converge towards the sink node. Other enhancement mechanisms may be envisioned too. For example, avoid sending data samples that can be predicted by the sink node following a certain forecasting algorithm. For query-driven applications, data may be made available at intermediate nodes such as cluster heads, in order to enhance the query/response process. Thus, when a query is sent, intermediate nodes can respond with the desired information. Finally, for event-driven model, a minimal routing infrastructure can be kept in order to maximize the lifetime of the overall network, since only few nodes can be used to relay data packets to the sink node.

2.5.2 Network Level Challenges

The main challenges at the network level are the dynamicity of the network topology and topology voids.

2.5.2.1 Changing Topology

MWNs are often assumed to be stationary. However, nodes mobility is sometimes needed in certain applications. Routing data packets may become very challenging since route stability is not guaranteed. Changes to the topology can also be the result of node failure due to energy depletion or physical damage. Energy conservation mechanisms such as wakeup/sleep scheduling may also result in a dynamic network topology. Moreover, the studied phenomenon can be dynamic (for example a moving target for a tracking application). In this case, the source node of the data is dynamic. Changes to the network topology can be categorized according to the node mobility into:

- *Stationary network*: in these networks, node failure due to energy depletion or hardware destruction is behind topology changes. The addition of new nodes is a source of topology changes too. Duty-cycling can also be result in a dynamic topology.

- *Mobile network*: nodes mobility results in intermittent connectivity. Nodes face then the appearing/disappearing of one-hop neighbours, making the forwarding decision very difficult. For delay-tolerant applications, nodes can store the data packets until the connexion with the destination node or a node that is certain or with high probability to reach the destination node. In less tolerant applications, routing protocols should handle this intermittent connectivity and include "*navigation*" functionality in order to let the data packets find easily their path towards the destination node across mobile nodes or messages ferries.
- *Hybrid network*: in hybrid networks, network topology dynamicity result from the above factors (nodes mobility, duty-cycling and nodes' failure).

2.5.2.2 Topology voids

Voids are regions where no nodes have been deployed or a region where no nodes are longer alive. Voids may also occur due to physical obstacles to radio communications. Handling topology voids may be very challenging for packet routing. Indeed, nodes need to detect such voids and must send data packets in a hop-by-hop basis in order to surround them. Topology control mechanisms need to deal with these voids efficiently in order to avoid that data packets arrive to dead-end nodes where no alternative forward path is available. Thus, routes heading to such topology voids need to be pruned sufficiently in advance. Figure 3 present an example of nodes facing a topology void.

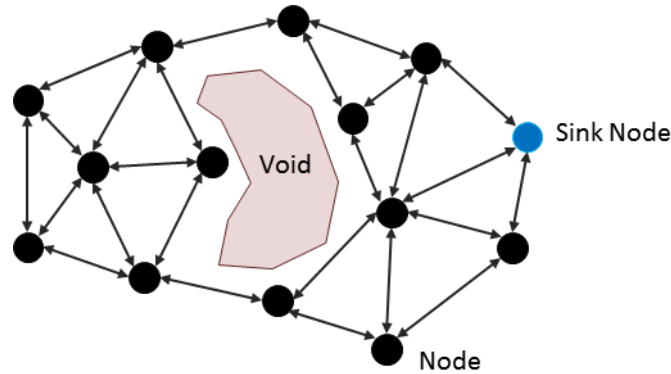


Figure 3: Presence of Void in the Sensing Field

2.5.3 Physical Level Challenges

MWN-based solutions are also facing various challenges at the physical layer such as link synchronisation, transmission scheduling, and link control. However, challenges faced at this layer of the communications protocol stack are out of the scope of this thesis and focus are given to high level layers' challenges as described in the previous sections.

2.6 Analysis of Routing protocols for MWNs

In this sub-section we present a brief overview of the main routing protocols for MWNs and especially WSNs [32][33] as we can find an impressive amount of routing protocols in the literature. A simple taxonomy is represented in Figure 4.

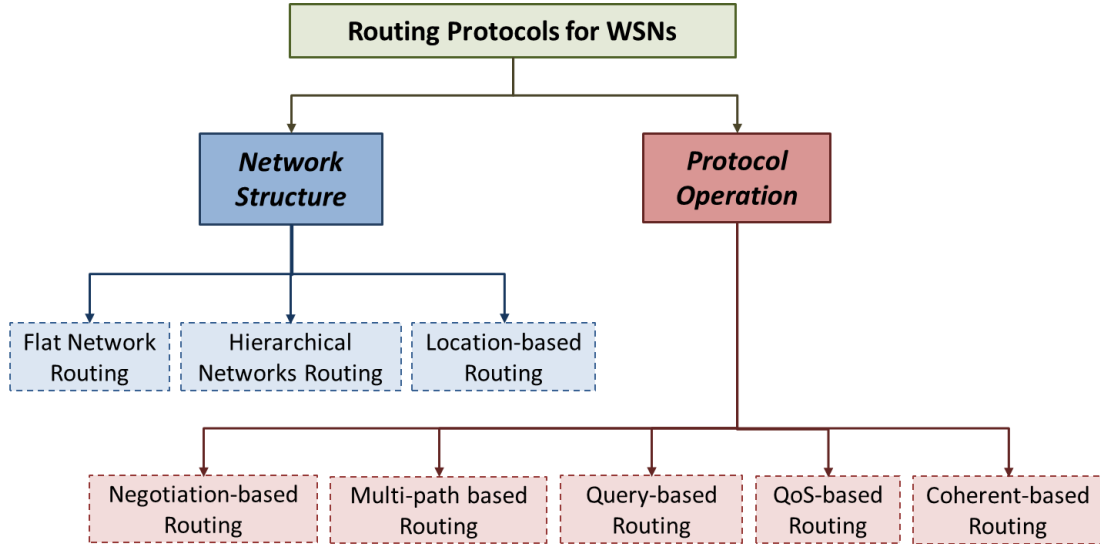


Figure 4: Taxonomy of Routing Protocols for WSNs.

First, routing protocols can be organized according to the network structure that the end-application is considering.

2.6.1 Network structure based routing protocols

The underlying networks structure can play an important role in the functioning of the routing protocol. If all the nodes composing the network are homogenous in terms of tasks, routing is considered flat. In the presence of node heterogeneity where nodes play different roles and have different capabilities such as group managers or cluster heads, routing is considered hierarchical. Finally when nodes rely on location information to perform packet forwarding decision, routing is considered location-based.

2.6.1.1 Flat routing

Flat routing is a multihop routing where all the nodes are operational and are affected the same tasks. In a flat topology, all the nodes cooperate in the data collection task. Due to the deployment of a large number of nodes, it may be not possible to address the nodes individually based on their identifier but regions of interest instead. This consideration is behind the data-centric routing. Early works include Directed Diffusion [34] and SPIN [35] protocols. These two protocols have influenced the design of many other protocols such as Rumor Routing [36], CADR [37], COUGAR [38], ACQUIRE [39], etc.

2.6.1.2 Hierarchical routing

Flat architectures do not offer a great scalability. Indeed, as the number of deployed nodes increases and the sensing field becomes wider, communications may become challenging. To achieve scalability, hierarchical network architectures have been proposed. In these architectures, nodes gather into groups or clusters and cluster-heads are elected. Special tasks are then affected to these cluster-heads. This organization allows energy efficiency since it reduces communications between cluster-nodes and other nodes of the network and data is collected, processed and transmitted by the cluster-head. Hierarchical routing protocols include LEACH [40], PEGASIS [41], TEEN [42], APTEEN [43], MECN [44], SAR [45], VGA [46], HPAR [47], TTDD [48], etc.

2.6.1.3 Location-based routing

In some applications, nodes are addressed using their location information. Thus, greedy forwarding can be employed using distance or angle calculus. Location information can be obtained from a specialized hardware such as GPS receiver or obtained using a distributed localization technique. In distributed mechanisms, nodes rely on signal strength, angle of reception, etc. in order to measure distances to landmark (that can be nodes with localization hardware). Such routing protocols include: GPSR [49], GAF [50], GEAR [51], MFR, DIR, GEDIR [52], GOAFR [53], SPAN [54], etc.

2.6.2 Protocol operation-based routing protocols

Based on the main operation of the protocol, routing protocols for WSNs can be organized into the following categories:

2.6.2.1 Negotiation-based routing

Negotiation-based routing protocols use high level data descriptors in order to reduce redundant data transmissions. SPIN [35] routing protocol falls into this category. The main idea behind such protocols is pre-transmission stage where nodes negotiate the data transmission using an advertisement/request mechanism. Thus, only interested nodes are requesting the data from the source node.

2.6.2.2 Multipath-based routing

In order to enhance routing performance, many routing protocols rely on the use of multiple paths. Multiple paths permit fault-tolerance since alternative paths exist in the case of the primary path failure. Multiple paths allow boosting the end-to-end route capacity in terms of bandwidth since parallel transmissions are possible. They also achieve lower end-to-end delays. However, the construction and the maintenance of multiple paths may introduce extra overhead in terms of control messages. Such protocols include TPGF [55], MPMPS [56], etc.

2.6.2.3 *Query-based routing*

In this case of routing protocols, the destination node (the node interested in certain information) sends a request to a certain node or a group of nodes. Nodes that have the requested data respond back with the desired information. These requests are often expressed in a high level language. Directed Diffusion [34] protocol falls into this category.

2.6.2.4 *QoS-based routing*

In this kind of protocols, nodes are trading energy consumption for a better quality of service in terms of lower end-to-end delays, transmission data-rate, etc. examples of such protocols include: SAR [57], SPEED [58], etc.

2.6.2.5 *Coherent-based routing*

Coherent and non-coherent data processing differ mainly in the location of data processing. In non-coherent data processing, collected data are treated locally at the source node before its transmission to the sink node. However, in coherent data processing, collected data is sent directly to an aggregator (i.e. a cluster-head) or to the sink node after minimum processing (i.e. value redundancy elimination). Thus, routing protocols that use one of the previous data processing are said coherent-based routing, or non-coherent-based routing [57].

2.7 Delay-Tolerant Routing in MWNs

In certain mobile deployment scenarios, connectivity can become very intermittent making classical protocols unusable. Applications must tolerate large delays or the risk of no forwarding guarantee. Such networks are called Delay Tolerant Networks (DTN). They mainly suffer from intermittent connectivity [59] and make use of opportunistic communications [60]. Routing in such networks is thus different from other wireless networks and is very challenging due to the frequent partitioning of the network. For example, routing protocols for wireless networks such as AODV [61] and DSR [62] may not be suitable for DTNs. Indeed, these protocols first establish a route between the source node and the destination node, and then data transmission actually occurs. If an instantaneous end-to-end path is hard to establish in DTNs, the store-carry-and-forward scheme should be used instead.

DTNs have the characteristic that, unlike standard networks, an end-to-end path between the source node and the destination node may not necessarily exist. However, it is desirable to allow communications between nodes. In this context, classic routing protocol cannot deliver efficiently data packets between the communicating nodes. Also, node mobility does not allow nodes to be aware of the current locations of node, especially if the mobility pattern is completely unknown.

Delay-tolerant networks have been used in various situations such as deep space communications, rural connectivity projects, city-wide ad-hoc networks, etc. DTN is also an approach for hybrid networks convergence. Unlike the work presented in [63], the DTN architecture presents an intermediate layer called the Bundle Layer that is located between the transport and the application layer in order to achieve convergence between different protocols stacks. The standard includes mechanisms for addressing, inter-node bundle transfer, security, etc.

The source of delay is mainly a result of 3 delays:

- *Processing Delay*: This is very short. It is the time necessary to process the packets header at the routers.
- *Queuing Delay*: This delay may be the longest. It is the time spent in routers queues waiting for transmission opportunity.
- *Transmission Delay*: This delay is wireless technology dependent. It is the time necessary for transmitting a data packet through the wireless link. This delay also includes the signal propagation delay which may be very significant. For example, it takes about 14 minutes for a radio signal to be propagated from Earth to Mars.

In the following sub-sections, we give a brief overview about routing strategies proposed for delay-tolerant networks. These strategies differ from each other in terms of the required knowledge about the network in order to perform routing decisions.

2.7.1 DTN Characteristics

Delay-tolerant networks differ from conventional wireless networks. They exhibit the following characteristics:

- *Intermittent Connectivity* [64]: DTNs networks suffer from network topology petitioning due to nodes mobility. In some DTNs nodes are more likely to be disconnected all the time and inter-nodes contacts occur very rarely. Moreover, these contacts are prone to transmission errors, making efficient contacts that lead to actual error-free data transmission rarer.
- *Opportunistic Communications* [65]: since connectivity is intermittent nodes achieves data packet forwarding through opportunistic contacts. These contacts can be scheduled and known in advance such as for deep space communications where the nodes dynamics is well-known in advance (planet movements, satellites, space-craft, etc.), or completely unknown and unpredictable such as moving people, vehicles, etc.

- *Limited Longevity*: Since DTNs networks can be deployed in much challenged environments (space, oceans, deserts, etc.), and due to long delays, the overall network lifetime can be very limited (energy depletion, attacks, physical damages, etc.)
- *Long Delays*: in DTN networks, an instantaneous end-to-end path may not necessarily exist. Thus the delay that separate the data generation at the source node and its reception at the destination node may be very long compared traditional networks. Queuing delay in intermediate nodes may compose the big part of this end-to-end delay.
- *Low Data Rates*: for some DTN scenarios, wireless links are used for very long distances. Thus they are very limited in terms of data rate. Moreover, transmissions errors may this data rate even lower. Also, such networks suffer from a low instantaneous data rate since nodes are often disconnected and no data transmission occurs.
- *Packet Delivery Rate*: as a result to the previous DTNs characteristics, packet delivery rates are also very low. Indeed, packet can be sent on a hop-by-hop across a network where a path may not exist towards the destination. Thus, packet loss is very common in multihop DTNs. In order to maximize the delivery probability, replication strategies have been widely used.

2.7.2 Routing Problem in DTNs

Most of routing protocols developed for delay-tolerant networks are designed using messages replication. With such strategy, a message is replicated across contacted nodes in order to maximize the probability of reaching the destination node. Functions are introduced to measure the willingness of a node to deliver the message to its final destination and forwarding decisions are made upon this willingness. Some functions need little or no knowledge about the network such as Epidemic routing protocol [66] where every contacted node is a good candidate to deliver the message and the routing is thus made through flooding.

To design an efficient routing protocol for delay-tolerant networks; some restrictions should be taken into account:

- *Resource Allocation* [67]: in DTNs nodes are more likely to store relayed data packets for long periods into their buffer queues, waiting for future contacts with other nodes. This restriction need to be carefully addressed, since received packets after queue saturation leads to their loss. Moreover, if message replication is considered,

resource may be then fewer across the networks, since copies of the same message may occupy queues at different nodes.

- *Buffer Space*: as stated above, nodes need to have sufficient buffer space to host all the potential data packets waiting for contact establishments due to intermittent connectivity.
- *Limited Energy*: DTN nodes are often deployed unattended, i.e. nodes are battery-powered. Communication task along the data processing and strong tasks may be very energy-consuming (sending/receiving over long distances, algorithms for contacts forecasting, maintaining large memory space, etc.). Thus routing protocol need to be designed with the energy-awareness for all tasks.
- *Contacts Availability* [68]: since DTN nodes are often disconnected, communications occurs through opportunistic contacts either scheduled/predictable or completely unpredictable.
- *Security Issues* [69]: security may be a very serious problem for DTNs [70]. Since data packets forwarding is delegated to nodes encountered in the network, sender and/or message authenticity should be guaranteed. Secure end-to-end routing is desirable.

2.7.3 Routing Topologies for DTNs

An important issue for routing in delay-tolerant network is the stability of the routing paths. The stability of a routing path may depend on various aspects such as the rate at which messages are generated at the source. The more frequent is message generation, the most unstable the routes will be, since it will be very difficult to find and maintain a route for a series of messages instead of a route for a single message. Thus, this route stability depends on the topological changes based on routing types:

- *Unicast Routing*: a source node will generate and send a single copy of the message. It will be in charge of finding the best path to reach the destination relying on the knowledge about the network topology.
- *Broadcast Routing*: a source generates a message and flooded it to all the nodes of the network. Every flooded node carries a copy of the message. The message delivery probability is very high in such routing.
- *Location-based Routing* [71]: data packets are forwarded greedily based on distance calculus in order to reduce the distance that separates the source and the destination node. However, there is no guarantee to reach the destination even if the distance is relatively small (absence of appropriate relay nodes, nodes mobility, etc.)

- *Tree-based Routing* [72]: Tree-based routing can be seen as enhancement of broadcast routing since it aims the reduction of the packet retransmissions. In this routing, the source flood the message through a tree structure routed at the source reaches all the receivers. Messages are replicated from parent node to child node.
- *Cluster-based Routing* [40][72]: nodes play different roles and special nodes are responsible for forwarding messages within determined clusters in order to increase message delivery.

2.7.4 Data Packet Forwarding Strategies

There are mainly two main categories of packet forwarding strategies: (1) forwarding-based strategies, and (2) replication-based strategies [73]. Figure 5 presents a classification of routing strategies for delay-tolerant networks.

2.7.4.1 Forwarding-based strategies

In forwarding-based protocols, only a single copy of the data packet is kept in the network during its transmission from the initial source to the final destination. Data packets are transmitted hop by hop through inter-node contact opportunities. These contacts depend on various factors such as weather conditions, radio link interference, etc. Routing for the forwarded-based strategies rely on the concept of custody-transfer where a node delegates the responsibility of the packet forwarding to another relay node, until it will reach the destination node.

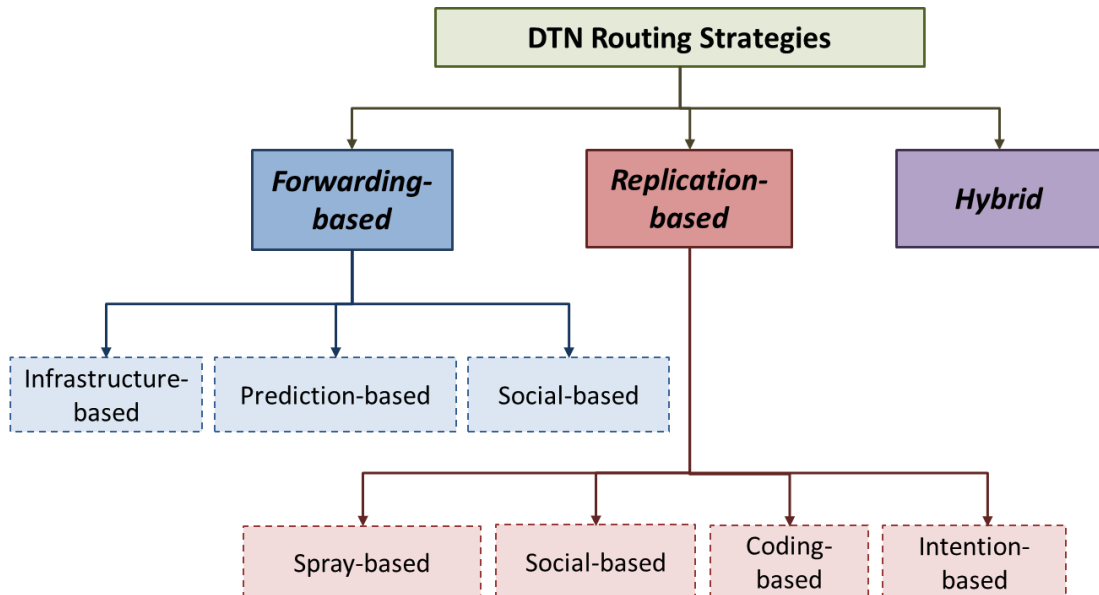


Figure 5: DTN Routing Strategies Classification

Forwarding-based strategies can be summarized into 3 classes:

2.7.4.1.1 *Infrastructure-based strategies*

In some applications scenarios, the mobility pattern of certain nodes may be known in advance. Infrastructure-based strategies propose the deployment of a fixed mobile infrastructure along the DTN nodes. Special mobile nodes (data mules) have been used as message ferries in order to connect partitioned and disconnected parts of the network [74][75][76]. These mobile nodes take messages from DTN nodes and move towards the destination node or the next relay node, and deliver the picked carried messages. Such strategy has been shown to be very efficient through extensive simulations in many research works. However, the deployment of an extra fixed/mobile infrastructure cannot be considered in many real DTN scenarios.

2.7.4.1.2 *Prediction-based strategies*

Prediction-based strategies have been employed in many routing protocols for DTNs. Such strategies aim to improve the routing performances through the calculation and the prediction of the future network state (next contact date, delivery probability, next contact duration, etc.). A typical routing protocol that uses prediction is PER [77]. PER predicts the message delivery based on the probability distribution of future contact dates and chooses the appropriate next forwarder aiming to enhance the packet delivery probability.

Prediction-based strategies are proven to behave better than traditional DTN routing schemes in terms of delivery ratio and end-to-end delay.

2.7.4.1.3 *Social-based forwarding strategies*

Mobility patterns have been widely analyzed. Researchers have found that some mobility patterns exhibit similar characteristics when compared to social networks. Thus, social relationships have been extensively investigated. These social mobility characteristics are employed in order to assist the routing decisions. Examples of such protocols that are based on social mobility model are SimBet [78], SSAR [79]. SimBet routing protocol makes explicit use of complex network analysis metrics and algorithms in order to highlight a node's position in the aggregated social graph, and assess its utility to act as a relay for messages destined to other nodes in the graph. SimBet assumes that nodes naturally reside in mobility-related communities (e.g., class, work, home). Thus, "well-connected" nodes in the network are chosen as message ferries to relay messages from one community to another, until a node that has many neighbors with the destination, (i.e., belongs to the destination's community) is reached.

In the other hand, SSAR routing protocol relies in the selfishness phenomenon of people for forward selection in real life. SSAR models the network as a weighted directed graph, where edges are given a weight that corresponds to the willingness of the start node to forward packets to the end

node. These weights are real numbers in $[0, 1]$. A 0 value means that a node is unwilling to forward packets to its connected neighbor whereas a 1 value means the connected neighbor will always be chosen to forward messages. Edges' weights are set randomly at the initialization of the network and then updated during the social changes.

2.7.4.2 *Flooding or Replications-based strategies*

Replications-based strategies require the relay nodes to keep a copy of the forwarded message in order to increase the message delivery probability by increasing the number of potential nodes that carry a copy of the message and that may encounter the destination node. This strategy can enhance greatly the delivery rate and reduce the end-to-end delay. However, this enhancement is made at the cost of network resources (memory, CPU, energy, etc.). Many research works have been carried out in order to optimize the replication-based strategies in order to achieve reasonable resource consumption. Epidemic Routing [66] is a well-known pure flooding-based routing protocol for DTNs. With Epidemic routing, each node transmits the message to all the nodes it encounters. Epidemic routing achieves a high delivery ratio reaching 100% if the storage space is unlimited. However, it performs poorly in networks with limited resources.

2.7.4.2.1 *Spray-based strategies*

In order to limit the replication of messages across all encountered nodes as done in Epidemic Routing, researcher studied and proposed protocols that limit the replication to some specific nodes. These protocols operate according to two stages. First, multiple copies are created and "sprayed" over the network. Then, each message copy is routed independently towards the destination node. To limit the overall retransmissions in the network, the number of message copies is relatively small and carefully decided. A well-known routing protocol that falls into this category is "Spray-and-Wait" [80]. Spray-and-Wait protocol consists of transmitting L copies of the originated messages to L different encountered nodes. These nodes will replicate the message to L other distinct nodes, and so on. After this "spray" phase, nodes will wait for direct forwarding, i.e. nodes will carry the message copy and wait until a direct contact with the destination node occurs. An enhancement has been proposed in [81] namely "Spray-and-Focus". In the "Focus" phase, nodes selects appropriate nodes based on utility function in order to forward a message copy to them. Such protocols have been shown to achieve good routing performances in terms of end-to-end latency and bandwidth overhead. Another enhancement is also proposed in [82].

2.7.4.2.2 *Social-based replication strategies*

As social-based forwarding strategies, social-based replication strategies make use of social network models along message replication to make routing decisions in order to increase the

message delivery rate and end-to-end delays. Such protocols include BUBBLE [83] and SocialCast [84]. BUBBLE uses the same social network model as SimBet. The data packet forwarding is divided into *global forward* and *inter-community forward*. SocialCast is a routing protocol which is based on the *publish-subscribe* concept. It relies on metrics of social interactions about nodes in order to determine the best relay node.

2.7.4.2.3 *Intention-oriented strategies*

Some proposed routing protocols for delay-tolerant networks treat routing decision as an optimization problem. RAPID [85] routing protocol falls into this category. RAPID models the data packet routing as a resource allocation problem, and expresses routing metrics as per-packet utility in order to determine how packets should be replicated in the system. For example, in order to minimize the average delay, the utility of a packet i can be expressed as $U_{pk_i} = -D(pk_i)$, where D is the accumulated delay. Replicating the packet to a certain node is then subject to the minimization of the accumulated delay so far and the increment in the delay if the message is sent through this encountered node. In [86] authors propose an energy-efficient forwarding algorithm based on epidemic routing. In this protocol, each message has its own energy constraint that is proportional to the number of expected transmissions in its life span in the network.

2.7.4.2.4 *Coding-based strategies*

In [87][88], data packets are fragmented and network coding is used in order to reduce resources consumption. In such protocols, data packets are fragmented into multiple fragments at the source node. These fragments are then replicated and broadcasted in the network. Intermediate nodes combine these fragments, encode them again and a new packet is retransmitted. Depending on the encoding algorithm, if the packet was initially encoded into k fragments, then the destination node can attempt to decode the original packet after receiving k different fragments. Though this method can use low buffer space, the routing may suffer from a longer delay if the k fragments fail to arrive at the destination node. However, coding-based strategies are proven to achieve good routing performances in the case of limited bandwidth and buffer space.

2.7.4.3 *Hybrid-based strategies*

Some research works have proposed the use of both forwarding and replication strategies simultaneously in one routing protocol. Such protocols aim to find the best trade-off between the high delivery rate brought by replication mechanisms and the resource efficiency brought by forwarding mechanisms. Such protocols include Max-Contribution [89] and HYMAD [90].

2.8 Self-Organization in MWNs

In certain scenarios, the physical deployed topology is not suitable for the well-functioning application. This underlying topology may be very resource inefficient in term of energy consumption. For example, in densely deployed networks, nodes may have a very large number of one-hop neighbors leading to radio transmission issues (interference, delays due to back-off algorithms) but also energy depletion due to intense radio activity.

Self-organization is the process through which nodes organize themselves autonomously into a logical network topology more efficient than the physical underlying topology. Self-organization aims to provide efficient, self-adaptive, scalable, fault-tolerant and robust communications protocols for dynamic and distributed multihop wireless networks.

Self-organization techniques can be classified into two main classes: (1) link pruning techniques where all the nodes are part of the logical topology and some links are "disconnected", and (2) dominating set techniques where only subset of nodes are composing the logical topology while the other nodes can be turned off.

2.8.1 Link pruning techniques

Due to the lack of centralized infrastructure in wireless multihop networks, and the dynamic topology, a fixed topology is not possible. The main goal of a topology control technique is then to construct an appropriate topology in order to overcome these issues. Link pruning algorithms rely heavily on geographic locations of nodes or on accurate distances between the nodes. In the following we present the main link pruning techniques self-organization.

2.8.1.1 Relative Neighborhood Graph

The Relative Neighborhood Graph (RNG) [91] H of a graph $G = (V, E)$ (Where V denotes the vertices set, and E the set of edges) is defined by $H = (V, E')$ where E' is the set of edges that obey to the following rule: "An edge that links two vertices u and v is part of H if and only if it does not exist any vertex w closer to both u and v ". This rule can be expressed as follows:

$$\forall u, v \in V: (u, v) \in E' \Leftrightarrow \nexists w \in V: \max(\overline{uw}, \overline{vw}) < \overline{uv}$$

Where \overline{uv} represents the Euclidian distance between the two vertices u and v . Thus, the RNG graph removes the longest edge in the triangle uvw (as shown in Figure 6).

RNG is a fully local algorithm since it only requires the knowledge of the one-hop neighborhood in order to construct the logical topology. However, the RNG algorithm relies on the knowledge of nodes locations or the distance between them, as well as the radio transmission

range. In [92] authors have shown that the minimum spanning tree (MST) is a sub-graph of the RNG. Thus, the RNG possesses the connectivity property of the initial graph (see Figure 12). RNG has also the characteristic to make two neighboring nodes in the physical topology very distant in the logical one. The average node degree in the RNG is close to 2.5 [93].

Link pruning algorithms are often used in geographical routing protocols [94]. They offer a planar graph which aids the selection of the next forwarder node. RNG is used in [95] in order to reduce the number of retransmission when flooding data packets in the network.

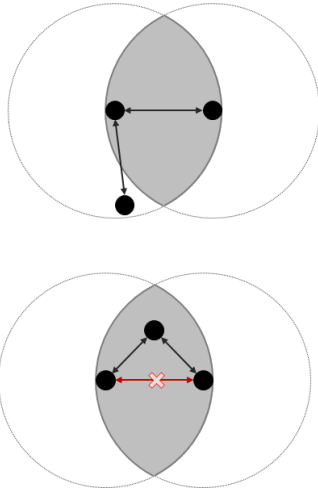


Figure 6: Link Pruning Mechanism in RNG

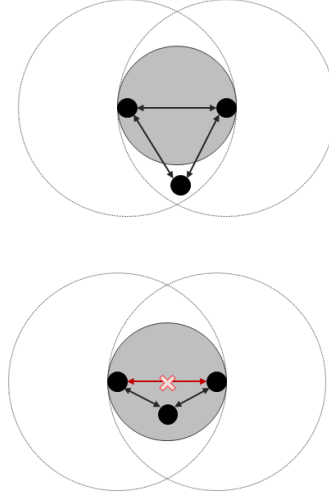


Figure 7: Link Pruning Mechanism in GG

2.8.1.2 Gabriel Graph

If we consider the disc $\mathcal{D}(u, v)$ with diameter uv , an edge is part of the Gabriel Graph (GG) [96] if and only if $\mathcal{D}(u, v)$ does not include any other vertex (cf. Figure 7). We can notice that RNG is a sub-graph of GG. Thus, GG preserves the connectivity property of the initial graph. A GG graph of 100 nodes is shown in Figure 11.

2.8.1.3 Delaunay Graph

Delaunay Graph (DG) is defined as the dual of the Voronoï diagram. A Voronoï diagram is the union of multiple Voronoï regions. A Voronoï region is defined as the region including all the points that are closer to a certain node x than any other node. Node x is implicitly put at the center of this region. From a Voronoï graph and for every pair of nodes whom Voronoï regions are adjacent, an edge is created between these two nodes in the Delaunay graph. Figure 8 shows an example of a Delaunay graph along a Voronoï diagram.

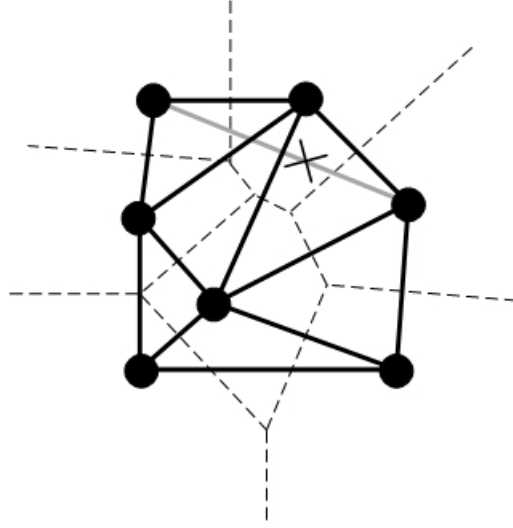


Figure 8: Delaunay Graph along Voronoï Diagram

2.8.1.4 Local Minimum Spanning Tree

A spanning tree is sub-set of a non-oriented convex graph that is a tree and does connect all the vertices. If a cost is assigned to each edge in the graph, the cost of the graph is then the sum of the edges costs. A spanning tree is said minimum if it has the smaller cost among the entire spanning trees of the graph. In this context, the cost of an edge is the Euclidian distance between the two nodes connected through it. With the Local Minimum Spanning Tree [97], every node computes its neighborhood minimum spanning tree (MST) using algorithms such as Prim Algorithm [98]. The LMST construction is governed by the following rule: "an edge between two nodes u and v is part of the LMST if and only if v is a neighbor of u in the MST of u , and if v is a neighbor of u in the MST of v (as shown in Figure 9). Finally the LMST topology preserves the connectivity of the initial graph (see Figure 13).

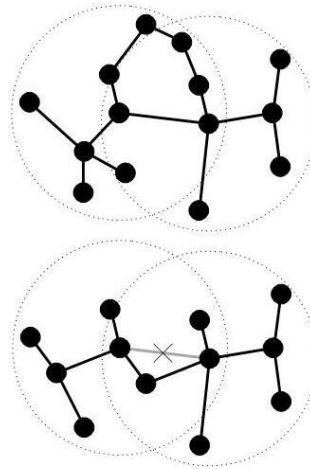


Figure 9: Link Pruning Mechanism in LMST.

It is worth to notice that LMST topology is achieved without global knowledge of the network. However, the LMST algorithm relies on accurate distance measuring between the nodes.

Many routing protocols rely on these link pruning techniques in order to guarantee the packet delivery by using a planar network topology.

2.8.2 Dominating Set Techniques

A Dominating Set (DS) of a graph is defined as a subset of nodes where each node is either part of this subset or it is a neighbor of a node that is part of this subset. This subset is called Connected Dominating Set (CDS) if the sub-graph based upon this subset is connected. CDS algorithms allow the reduction of hop count between the source and the destination. Constructing CDSs with minimum cardinality is NP-Hard problem. Thus, many heuristics have been proposed to compute such subset. An example of a connected dominating set according to [99] is shown in Figure 15.

The main Dominating Set techniques are:

2.8.2.1 *Multipoint Relay and Multipoint Relay Dominating Set*

Multipoint Relay (MPR) has been proposed in [100] and it is behind the standardized routing protocol Optimized Link State Routing (OLSR) [101]. Authors used the resulting dominating set in order to reduce the number of packet retransmission in flooding operations. In order to construct the MPR nodes subset, each node selects among its neighbors, the nodes that allow reaching all 2-hop neighbors. These neighbors are called MPR nodes.

In order to build a topology that is connected and dominating, every MPR node retransmits a topology construction control packet while pointing out its MPR nodes in its local neighborhood. Thus, the designation of MPR nodes is localized. However, the construction of the dominating set is distributed across the network and depends on the considered source node.

MPR-Dominating Set (MPR-DS) [102] uses the same relay selection as in MPR. However, in order to avoid the dependence toward a source node that initiates the topology construction, it is based upon nodes identifiers leading to a totally distributed algorithm independent from the source node. A node is part of the dominating set if: (1) its identifier is the smallest among its direct neighbors, or (2) it has been designated MPR node by the neighboring node with the smallest identifier.

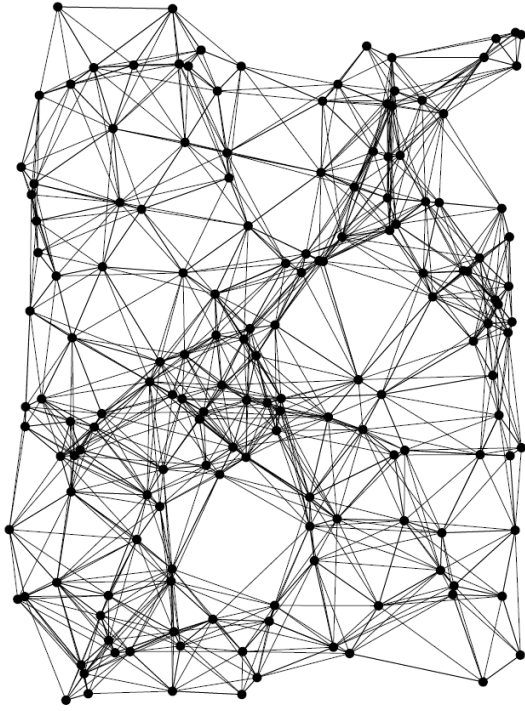


Figure 10: Initial Unit Disc Graph[103]

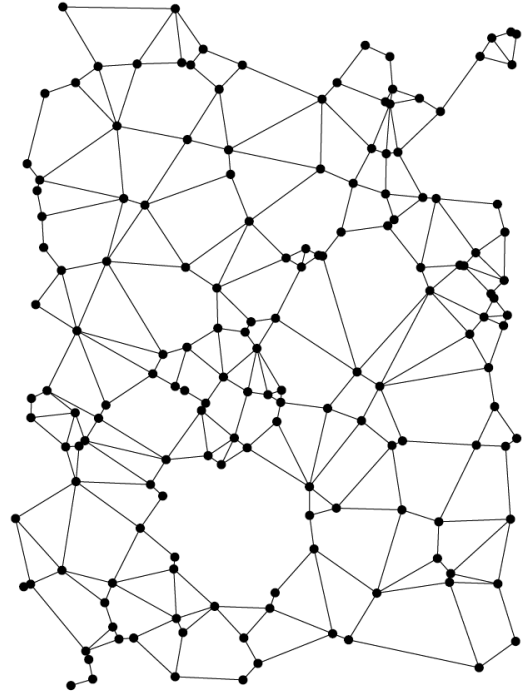


Figure 11: Gabriel Graph (GG) [103]

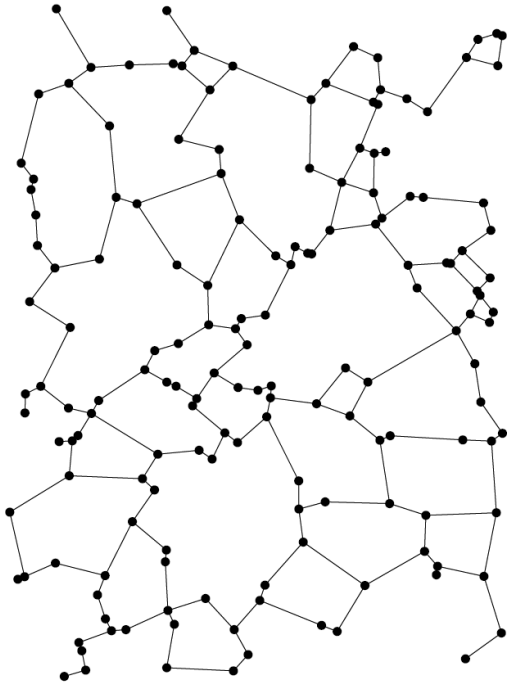


Figure 12: Relative Neighbour Graph (RNG) [103]

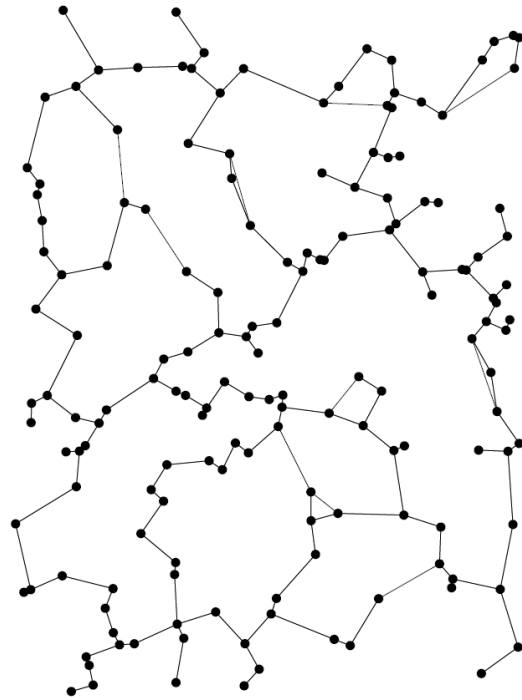


Figure 13: Local Minimum Spanning Tree (LMST) [103]

2.8.2.2 Connected Dominating Set – Rule k

Dai and Wu [99] proposed a localized construction of the CDS. This proposed algorithm operates through two stages. The first stage concerns the marking of the nodes, while the second stage concerns link pruning according to a rule named "*rule k* ". Basically, a coverage of a node can be withdrawn of its neighbor set can be collectively covered by those of k coverage nodes.

These k coverage nodes have higher priority and are connected. Moreover, the CDS derived from the marking process with *Rule k* can be locally maintained, when sensors switch-on/off.

2.8.2.3 Connected Dominating Set – Independent Dominating Set

Authors in [103] propose the construction of a CDS-ID. A dominating set is called independent if each node part of this subset is not adjacent to another node that is also part of this subset. Thus, nodes that are part of IDS are exactly 2-hops away from each other. This algorithm operates through 3 steps: (1) construction of the spanning tree, (2) construction of the IDS, and (3) construction of the dominating tree. The proposed algorithm is totally distributed. Since, the dominating set is constructed after a network discovery phase; this algorithm achieves a better selection of the nodes to be part of the connected dominating set.

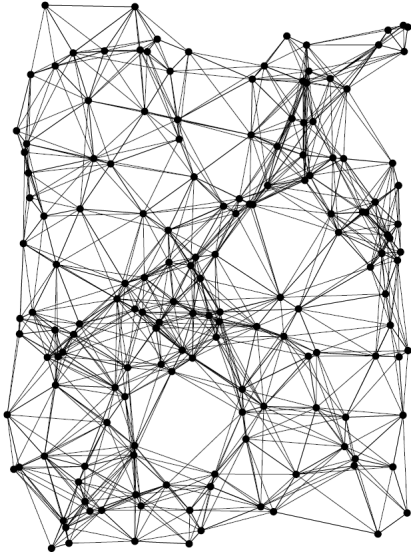


Figure 14: Initial Unit Disc Graph[103]

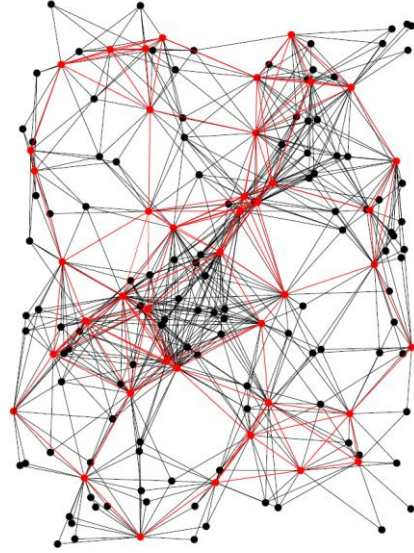


Figure 15: Connected Dominating Set[103]

Self-organization techniques which are based on either connected dominating sets or link pruning, aim to overcome the inefficient physical topology resulting from network deployment. These techniques build a logical topology upon the physical one in order to reduce the energy consumption.

2.9 Conclusion

In this chapter, we have presented a brief state of the art of challenged multihop wireless networks. We first, gave an overview of the potential application that can be considered using these networks.

After a brief description of the architecture of a wireless node, we presented the different characteristics of these networks. These networks are generally application-specific and easy to deploy. They are self-organizing and function unattended. Their network topology is often dynamically changing, and exhibit traffic convergence towards a central entity called the sink node.

In the second part, we presented the general challenges and design principles that application design should consider carefully. Thus application developed for such networks should be fault-tolerant, scalable, and energy-aware. Also, at the node level, hardware constraints and manufacturing cost should be taken into account. After that, we present a simple taxonomy of some challenges according to their level in the communication stack, mainly application specific challenges and network specific challenges. The first class includes challenges related to the quality of service, bandwidth and the data delivery model, while the second class includes challenges related to the changing network topology and topology holes.

Then, we present taxonomy of routing protocols for WSNs as an example of challenged MWNs where energy utilization is at the heart of the application functionalities design and especially the routing functionality. For QoS-based applications, multipath routing can be of good choice. However, most of the surveyed protocols rely on important control traffic for the topology discovery and the routing path construction and maintenance. This overhead may lead to routing inefficiency.

DTNs are another example of challenged MWNs, where delay is at the centre of the application design. We start by presenting these networks and their characteristics, then we present taxonomy of routing protocols proposed for DTNs. However, a lot of these protocols rely on replication-based schemes or extended knowledge about the network topology in order to perform routing decisions.

Finally, multihop wireless network self-organization is presented and state-of-the art techniques are reviewed. These techniques agree to construct an efficient logical topology upon the physical network.

Chapter 3

3 Online Multipath Routing in Multi-hop Wireless Networks

3.1 Introduction

With the advancement in miniaturization and the availability of low-cost hardware, the computing nodes embed various kinds of sensing and capturing elements including microphones and video cameras. Hence, the use of ubiquitous Wireless Multimedia Sensor Networks (WMSNs) is becoming a reality [4][105][106][107].

WMSNs are generally used for surveillance applications, intrusion detection, environmental and building monitoring, etc. These applications imposes additional challenges such as energy-efficient data processing both within node and in-network, audio/video bandwidth/rate adaptation to overcome the variations in networking conditions, Quality of Service (QoS) delivery to meet application specific requirements and routing and selecting appropriate paths for continual delivery of multimedia streams. Due to the distributed and dynamic nature of these types of networks, the design of a critical information infrastructure based on a WMSN raises many other challenges such as ensuring confidentiality and the integrity of the data stream, providing the means for node authentication and access control, securing routing and node grouping [108]. Among all these challenges, our work focuses on the routing and path selection issues taking into account energy constraints and QoS delivery needs.

Generally, routing in wireless sensor networks (WSN) is a challenging task. A comprehensive survey of routing protocols in WSN is given in [105]. A large number of research works exists to enable energy efficient routing in WSN. In fact, we can find different routing techniques that try to achieve energy-efficiency and to provide a best quality of service. One example is the multi-channel transmission in WMSNs. In [109], authors have evaluated the performances of routing (routing delays) when using a single and multi-channel communications in a wireless sensor and actor networks. The authors showed that the multi-channel scheme performs better than the single channel scheme especially for higher volumes of generated traffic putting the light on the important need to parallel transmissions in a wireless multimedia sensor network, where delay and packets loss are stringent constraints. Even in IP networks, multimedia transmission is still challenging. Although the use of traffic prioritization in DiffServ networks, end-to-end throughput is not guaranteed, application can make use of dynamic content adaptation based on end-to-end path

measurement [110][111]. In wireless IP networks, when data transmissions are prone to errors, application can make use forward error-correction mechanisms in order to cope with random packet loss [112][113].

In higher layers of the communication protocols stack, performances evaluations of routing protocols for WMSNs suggests multipath routing approach to maximize the throughput of streaming multimedia traffic. This is to utilize diverse paths to route packet streams towards the destinations in order to avoid draining the energy of nodes along a specific route. In [114], the authors propose a multipath routing protocol based on the well-known routing protocol Directed Diffusion [33] that reinforces multiple routes with high link quality and low latency. In [115], the authors focused on two key questions regarding multipath routing in WMSNs: (a) how many paths are needed? And (b), how to select these paths? The authors then proposed a multipath routing mechanism in order to provide a reliable transmission environment with low energy consumption by utilizing the energy availability and the received signal strength of the nodes to identify multiple routes from the source to the destination. In [116], the author addresses the problem of interfering paths in a WMSN and considers both intra-session as well as inter-session interferences. The author proposes an incremental path creation mechanism where additional paths are set up only when required (typically in case of congestion or bandwidth shortage). In [117], authors propose MCMP (MultiConstrained MultiPath) routing protocol in order to guarantee a better QoS in terms of delay and reliability. Unlike end-to-end QoS schemes used in WSNs, the authors utilize a multiple paths creation mechanism based on local link information.

Other examples of multipath routing protocols for WMSNs include: MPMPs (*Multi-Priority Multi-Path Selection*) [56] and TPGF (*Two-Phase Geographical Greedy Forwarding*) [55]. However, these “offline multipath” protocols have to explore the multiple routes that may exist between the source and the destination before the actual data delivery phase. They may not be well adapted for large-scale highly dense network deployments and for networks with frequent node mobility.

Geographic routing is the process in which each node is aware of its geographic coordinates and uses the position of packet’s destination to perform routing decisions. These types of routing scales better for WSNs. Greedy Perimeter Stateless Routing (GPSR) [49] was defined as a geographic routing protocol in order for the network to scale in large size networks, i.e., to accommodate a large number of nodes having very low exchange of route state information and maintenance. The advantage of this protocol is that each node only gathers the topology information about its immediate neighbours. Thus, its greedy forwarding relies on local-knowledge for selecting the closest next hop node to the destination. This process ends up with continuous

selection of the same path that leads to fast depletion of the energy of the nodes along the selected route and premature dying of these nodes.

In this chapter, we examine the benefit of geographic routing along with “online” multi-path route selection process (i.e. multiple routes are created as packets advance towards the destination) and propose a new routing protocol called AGEM (Adaptive Greedy-compass Energy-aware Multipath) that takes into account both node’s energy constraints and QoS needs of audio and video streams.

The design of AGEM is driven by the following factors:

Alternative paths: multimedia applications are delay sensitive and have delay and delay variation constraints. Multimedia traffic should be delivered satisfying these requirements. In typical networks, shortest paths are heavily used for the delivery of this traffic types whereas other appropriate routers that could satisfy these traffic requirements are under-utilized.

Load balancing: In order to maximize the lifetime of WSN nodes and to avoid depletion of nodes’ energy and consequently node’s failures, load balancing and multi-path delivery across the network must be considered during the design of a routing protocol.

Multipath transmission: Packets in a multimedia stream are generally large in size and the transmission requirements can be several times higher than the maximum transmission capacity of sensor nodes if a single path is used for routing these packets.

Online decisions: As the topology may change from time to time, it is more appropriate to make the routing decisions in a distributed manner and in real-time. This is due to the fact that offline routing processes cannot react to topology changes and result in forwarding packets to unavailable nodes or towards disconnected routes.

Node selection process: in densely deployed networks, different neighbours may be selected as candidate for packet forwarding. To deduce an appropriate selection, the node selection process should take into account, node’s energy, its distance to the destination, and packet’s QoS requirements.

The rest of this chapter is organized as follows. Section 3.2 reviews the related work in the area of WSN routing that influenced the design of our proposed protocol. Section 3.3 presents the functionalities of proposed AGEM protocol. Section 3.4 provides the results of performance evaluations of our proposed protocol in comparison with GPSR. Finally, section 3.5 presents our conclusions.

3.2 Related Work

In geographic routing, two greedy schemes are used to make packets progress towards the destination node. Greedy progression scheme based on distance to the destination node [49][118][119][120] and greedy progression based on angular offset in the direction towards the destination node [121][122][123]. In both schemes, a route between source and destination is progressively chosen only based on node-level forwarding decisions made locally at each hop.

For WMSNs, two important protocols have been proposed that make use of node positions for packet forwarding i.e., GPSR and MPMPs. MPMPs is itself based on TPGF. These protocols are further explained below.

3.2.1 The GPSR Routing Protocol

The GPSR (*Greedy Perimeter Stateless Routing*) [49] was originally designed for MANETs but rapidly adapted for WSNs. The GPSR algorithm relies on the correspondence between the geographic location of nodes and the connectivity within the network by using the location position of nodes to forward a packet. Given the geographic coordinates of the destination node, the GPSR algorithm forwards a packet to destination using only one single hop location information. It assumes that each node knows its geographic location and geographic information about its direct neighbours.

GPSR protocol uses two different packet forwarding strategies: *Greedy Forwarding* and *Perimeter Forwarding*. When a node receives a packet destined to a certain node, it chooses the closest neighbour out-of itself to that destination and forwards the packet to that node. This step is called the *Greedy Forwarding*. In case that such node cannot be found, (i.e. the node itself is the closest node to the destination out-of its neighbours but the destination cannot be reached by one hop), the *Perimeter Forwarding* will be used. The *Perimeter Forwarding* occurs when there is no neighbour closest to Destination (D) than node (A) itself. Figure 16 illustrates that node A is closer to D than its neighbours x and y. This situation is called “voids” or holes. Voids can occur due to random nodes deployment or the presence of obstacles that obstruct radio signals. To overcome this problem, *Perimeter Forwarding* is used to route packets around voids. Packets will move around the void until arriving to a node closest to the destination than the node which initiated the *Perimeter Forwarding*, after which the *Greedy Forwarding* takes over.

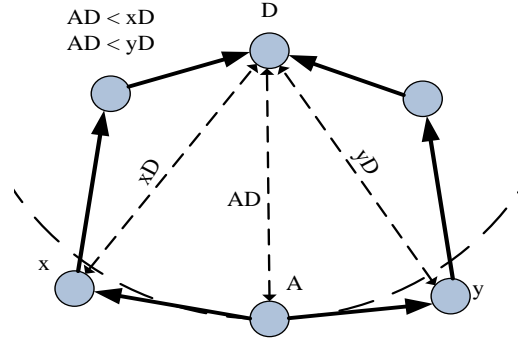


Figure 16: GPSR Perimeter Forwarding to Bypass a Void.

By maintaining only information on the local topology, the GPSR protocol can be suitable for WSNs. However, the greedy forwarding leads to choose only one path from the source to the destination.

3.2.2 The TPGF Routing Protocol

TPGF (*Two Phase geographical Greedy Forwarding*) [55] routing protocol is the first to introduce multipath concept in wireless multimedia sensor networks (WMSNs) field. This algorithm focuses in exploring and establishing the maximum number of disjoint paths to the destination in terms of minimization of the path length, the end-to-end transmission delay and the energy consumption of the nodes. The first phase of the algorithm explores the possible paths to the destination. A path to a destination is investigated by labelling neighbours nodes until the base station. During this phase, a step back and mark is used to bypass voids and loops until successfully a sensor node finds a next-hop node which has a routing path to the base station. The second phase is responsible for optimizing the discovered routing paths with the shortest transmission distance (i.e. choosing a path with least number of hops to reach the destination). The TPGF algorithm can be executed repeatedly to look for multiple node disjoint-paths. It's worth to note that TPGF is an offline multipath routing protocol.

3.2.3 The MPMPs Routing Protocol

The MPMPs (Multi-Priority Multi-Path Selection) [56] protocol is an extension of TPGF. MPMPs highlights the fact that not every path found by TPGF can be used for transmitting video because a long routing path with long end-to-end transmission delay may not be suitable for audio/video streaming. Furthermore, because in different applications, audio and video streams play different roles and the importance level may be different, it is better to split the video stream into two streams (video/image and audio). For example, video stream is more important than audio stream in fire detection because the image reflects the event, audio stream is more important in deep ocean monitoring, while image stream during the day time and audio stream during the night

time for desert monitoring. Therefore, we can give more priority to the important stream depending on the final application to guarantee the using of the suitable paths.

3.2.4 Policies for Greedy forwarding

In literature, there are different policies that can be used in geographic routing and for the selection of the next hop node. To illustrate these policies, let take ' u ' as the current forwarder node and ' d ' the destination node, then we can define these routing policies (see Figure 17):

Compass routing: See Figure 17(a) – The next relay node is ' v ' such that the angle $\angle vud$ is the smallest among all neighbours of ' u ' [121].

Random compass routing: See Figure 17(b) – Let ' v_1 ' be the node above line (ud) such that $\angle v_1ud$ is the smallest among all such neighbors of ' u '. Similarly, define ' v_2 ' to be node below line (ud) that minimize the angle $\angle v_2ud$. Then, node ' u ' randomly chooses ' v_1 ' or ' v_2 ' to forward the packet [121].

Greedy routing: See Figure 17(c) – The next relay node is ' v ' such that the distance $\|vd\|$ is the smallest among all neighbours of ' u ' [124].

Most forwarding routing (MFR): See Figure 17(d) – The next relay node is ' v ' such that $\|v'd\|$ is the smallest among all neighbours of ' u ', where ' v ' is the projection of ' v ' on segment ud [124].

Nearest neighbour routing (NN): See Figure 17(e) – Given a parameter angle ' α ', node ' u ' finds the nearest node ' v ' as forwarding node among all neighbours of ' u ' in a given topology such that $\angle vud \leq \alpha$.

Farthest neighbour routing (FN): See Figure 17(f) – Given a parameter angle ' α ', node ' u ' finds the farthest node ' v ' as forwarding node among all neighbours of ' u ' in a given topology such that $\angle vud \leq \alpha$.

Greedy compass: Node ' u ' first finds the neighbours ' v_1 ' and ' v_2 ' such that ' v_1 ' forms the smallest counterclockwise angle $\angle duv_1$ and ' v_2 ' forms the smallest clockwise angle $\angle duv_2$ among all neighbors of ' u ' with the segment ud . The packet is forwarded to the node of $\{v_1, v_2\}$ with minimum distance to ' d ' [125][122].

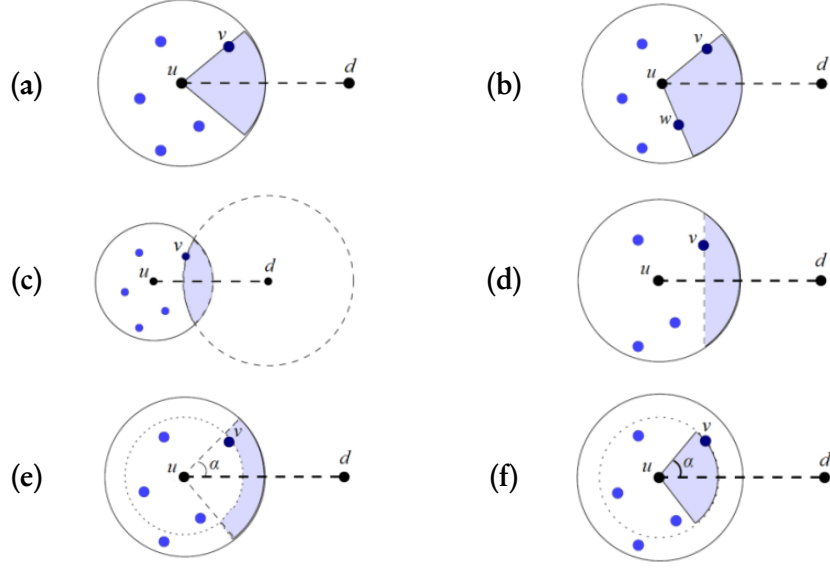


Figure 17: Greedy Forwarding Strategies: (a) Compass Routing; (b) Random Compass Routing; (c) Greedy Routing; (d) Most Forwarding; (e) Nearest Neighbour Routing; (f) Furthest Neighbour Routing.

3.2.5 Discussion on Routing/Forwarding

Paths are selected a priori by protocols such as TPGF and MPMPs. In such cases, paths are chosen in advance from the source to the destination. Knowing the full map of the deployed network to perform routing as done by most “*offline multipath*” routing protocols is not suitable for many reasons: (1) the exchange of the network map is energy consuming, (2) the map may not reflect the current network topology, and (3) nodes’ failure can be more frequent in WSN than in other ad-hoc networks. These reasons cause routing problems. In GPSR protocol, packets are forwarded hop by hop based on information available local to node i.e., the use of “*Greedy routing*” policy. GPSR seems to be more promising to scale to large network but does not achieve load balancing by making use of multiple routes.

Hence, we propose a new geographical and online routing protocol called AGEM that (1) selects neighbour nodes using an adaptive compass mechanism which is a newly defined policy, (2) routes packets on multiple paths using greedy routing policy for load balancing purposes, and (3) avoids network holes using walking back forwarding.

3.3 AGEM Routing Protocol

The main idea behind AGEM[126][127] protocol is to include a load-balancing feature while being a greedy geographic routing protocol in order to increase the lifetime of the network and to reduce the queue size in the most used nodes across the network. While using a pure greedy routing protocol like GPSR, data/video streams always use the same route. In AGEM routing protocol, data/video streams are routed using different paths. At each hop, a forwarder node decides to

which neighbour to send the packet. The forwarding policy at each node is based on the following four parameters: (1) the residual energy at node, (2) the number of hops visited by the packet before it arrives at this node, (3) the distance between the node and its neighbours, and (4) the history of the packets forwarded belonging to the same stream. Furthermore, only a subset of available neighbours is chosen according to the new adaptive compass selection mechanism.

The AGEM routing protocol has two modes, the *Smart Greedy Forwarding* and the *Walking Back Forwarding*. The first mode is used when there is always a neighbour node closer to the destination node than the forwarder node. The second mode is used to get out of a blocking situation in which the forwarder node can no longer forward the packet towards the destination node. Figure 18 presents an overview diagram of AGEM routing mode switching.

The following section will explain the two routing modes.

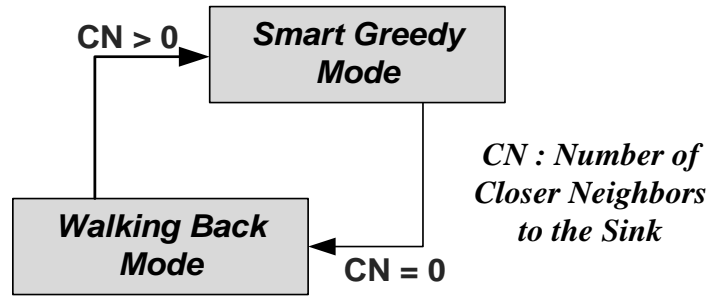


Figure 18: GEAMS Routing Mode Switching.

3.3.1 Smart Greedy forwarding mode:

AGEM is a geographic routing protocol where the nodes are aware of their geographic coordinates. This information can be obtained using a positioning system such as GPS or by using distributed localization techniques such as DV-Hop [128], Amorphous [129], etc.

In AGEM routing protocol, each sensor node keeps track of related information about its *immediate* neighbours and stores the information that includes the estimated distance to its neighbours, the distance of the neighbour to the destination, the data-rate of the links, and the remaining energy of neighbours. This information is updated by the mean of beacon messages propagated locally, scheduled at fixed adjustable intervals. Relying on this information, a forwarder node will give a score to each neighbour according to a function (i.e. $f(x)$).

Since AGEM protocol is an online protocol and relies on beacon exchange for neighbourhood state maintenance, AGEM can be used for static or mobile sensor networks.

Since AGEM routing algorithm is based on geographic coordinates, distance-based greedy progression is used along angle-based greedy progression for next hop node selection. So, not all the

neighbours closest to the destination than the forwarder node are going to be selected as the candidates for packet forwarding. This set of nodes is reduced to only include those nodes with best angular offset towards the destination.

At the beginning, the forwarder node chooses only neighbour nodes that are within an angular (α) view towards the destination with an initial angle of α_0 (e.g., $\alpha = \alpha_0 < 30^\circ$). A minimum of “ n ” neighbour nodes (neighbouring set with $n \geq 2$) must be found to perform load balancing. If $n=1$ then there is just one node set where no load balancing can be achieved. If no node is found, the angle α is incremented by $\Delta\alpha$ (e.g., $\Delta\alpha = 10^\circ$) until it reaches 180° . At this stage, if no node is found then a walking back forwarding is needed since the forwarder is facing a hole. Figure 19 illustrates this adaptive forwarding policy. The angle of view is chosen small and incremented until finding the desired number of candidates' nodes. This way, the selected nodes will always have the least angular offset from the line (src) \rightarrow (dst). Moreover, these selected nodes are then ordered according to their given score.

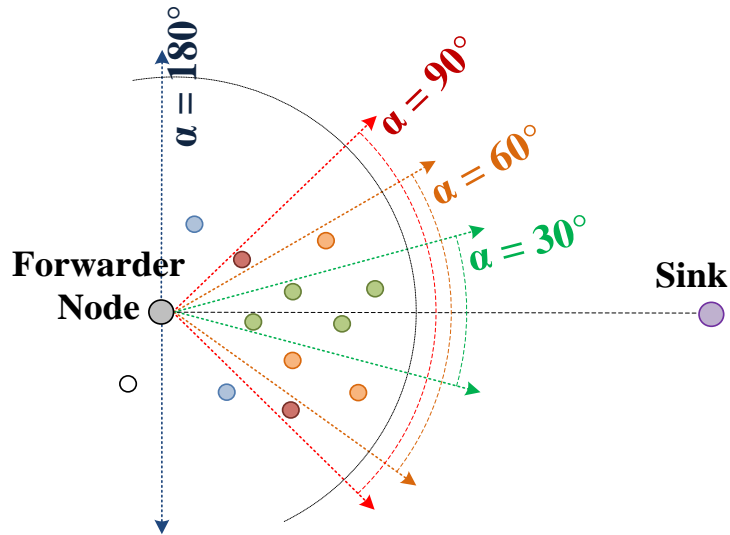


Figure 19: AGEM Adaptive Compass Policy.

Choosing a node from the neighbouring set to forward a packet will depend on the score given to each node according to the “ $f(x)$ ” function (see Figure 20). The $f(x)$ considers the energy consumption which is defined in the following subsection.

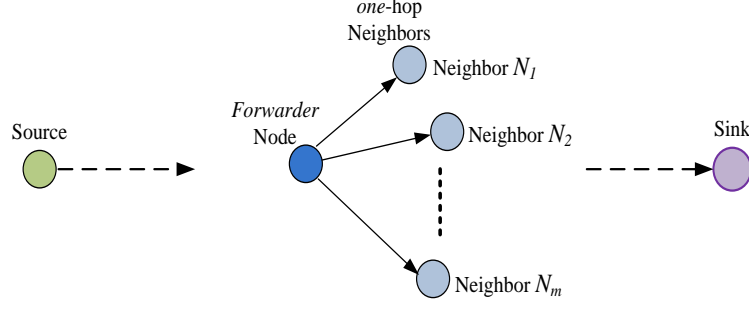


Figure 20: One-hop Neighbours Sorted According to their Scores.

3.3.1.1 Packet energy consumption :

When a node (A) sends a packet (pk) of n bits size to a node (B), the energy of node (A) will decrease by $E_{TX}(n, \overline{AB})$ while the energy of the node B will decrease by $E_{RX}(n)$. Consequently, the cost of this routing decision is $E_{TX}(n, \overline{AB}) + E_{RX}(n)$ considering the energy of the whole network. Figure 21 illustrates this energy consumption.

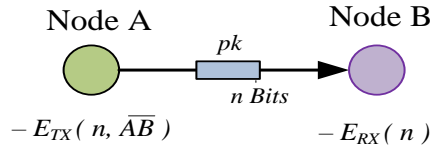


Figure 21: Packet Energy Consumption between two Communicating Nodes A and B.

We assume that the transmitted data packets in the network have the same size. We propose an objective function to evaluate a neighbour N_i for packet forwarding. This objective function takes into account the packet energy consumption and also the initial energy of that neighbour. The proposed objective function can simply be:

$$f(N_i) = N_{i_Energy} - E_{TX}(N_{i_Distance}) - E_{RX}$$

Where: $E_{TX}(D)$ is the estimated energy to transmit a data packet through a distance D , and E_{RX} is the estimated energy to receive the data packet.

These two functions rely on the energy consumption model proposed by Heinzelman *et al* [130]. According to this model, we have:

$$E_{TX}(k, D) = k \cdot (E_{ELEC} + \varepsilon_{amp} \cdot D^2)$$

$$E_{RX}(k) = k \cdot E_{ELEC}$$

Where: k is the size of the data packet in bits, D is the transmission distance in meters, E_{ELEC} is the energy consumed by the transceiver electronics, ϵ_{amp} is the energy consumed by the transmitter amplifier. E_{ELEC} was taken to be $5 \mu J/bit$ and ϵ_{amp} $1 \eta J/bit$.

Upon receiving a data packet from the source node s_i , the forwarder node retransmits the packet to a neighbour that is closest to the destination node and in such a way that the number of hops the packet traversed, will meet the rank of that neighbour (neighbours are ranked according to their score). The main idea is to forward a packet with the biggest number of hops through the best neighbour, and consequently a packet with the smallest number of hops is routed through the worst neighbour to allow a proper load balancing in the network (see Figure 23 and Figure 24). Figure 22 describes an algorithm as the forwarding policy.

For each known source node s_i a forwarder node (N) maintains a pair (H_i, j) . H_i represents the mean hop count that separates s_i from N , and j represents the neighbour (N_j) whom score (i.e. $f(x)$ function) is closest to the average score of all closest nodes to the sink in the neighbour set (called best neighbour set).

As shown in Figure 22, the algorithm checks (Line 1) if a packet is already received from a source node. If no, the packet will be always forwarded to the best node (line 2), and the hop count “H” and the average score index “j” in the best neighbour set are set. These empirical values will be used later to allow load balancing. It is clear that the first packet received from an unknown source will be always forwarded to the best neighbour node.

Upon_Recieving_a_Packet (pk)

Parameters:

Best_Neighbor: a set of the closest neighbours to the sink node sorted in descending order by their score $\{BN_1, BN_2, \dots BN_m\}$.

$m = |Best_Neighbor|$. m represents the cardinal of the *Best_Neighbor* set

j : index of the node in the set **Best_Neighbor** whom score is closest to the average score of all closest nodes to the sink. For example, if **Best_Neighbor** is $\{8,5,2,1\}$ the average score is 4 then $j=2$ (starting from index=1)

Functions:

Get_Hop_Values (S_i) returns the stored values of empirical hop count from already known source S_i and the j index of the average score of all closest nodes to the sink. These values are (H_i, j)

Set_Hop_Values (S_i, H_i, j) sets the empirical hop count for source S_i to be H_i and j to be the index of the average score of **Best_Neighbor** set.

Forward (pk, BN_k) forwards the packet pk to the neighbour k which has BN_k score

01:	if (Get_Hop_Values (<i>pk</i> .SourceNode) is Null) {
02:	Forward (<i>pk</i> , BN[1]) <i>// Default forward to best node</i>
03:	H ← <i>pk</i> .HopCount
04:	Set_Hop_Values (<i>pk</i> .SourceNode, H, j)
05:	}
06:	else { <i>//Get_Hop_Values (pk.SourceNode) is not null</i>
07:	(H, j) ← Get_Hop_Values (<i>pk</i> .SourceNode)
08:	$\Delta h \leftarrow H - pk.HopCount$
09:	index ← j + Δh
10:	case (index ≤ 0) {
11:	H ← H - index + 1
12:	index ← 1 <i>// index of the best node in Neighbor_Set</i>
13:	}
14:	case (index > m) {
15:	H ← H - index + m
16:	index ← m <i>// index of the worst node in Neighbor_Set</i>
17:	}
18:	Forward (<i>pk</i> , BN[index]) <i>// Smart forward</i>
19:	Set_Hop_Values (<i>pk</i> .SourceNode, H, j)
20:	}

Figure 22: The Smart Greedy Forwarding Algorithm.

Line 7 specifies that we have already an empirical estimation of the hop count H and the average index j from a particular source. These values are retrieved as shown in line 8. We calculate (in line 9) the deviation Δh of the hop count of the received packet compared to the stored value H . The index of the new forwarder neighbour that allows best load balancing will be adjusted by Δh (line 10). However, two different out of range situations may occur. Line 11 specifies that the received packet has passed through a lot of hops, and thus it needs to be forwarded to the best node (i.e. node with index=1). The received packet that has experienced a less hop count than the empirical value H (line 15), and thus it has to be forwarded to node with higher index (index= m). The new empirical value is computed (Line 12 and 16) that will be used later as a new reference. Finally, the packet is forwarded by using the described *Smart Greedy Forwarding* (line 19).

3.3.2 Walking Back forwarding mode

Because of node failures, node energy depletion due to processing and scheduling activities and node mobility, disconnections may occur in a WSN generating what we call “voids”. At certain times, a forwarder node may face a void where there is no closest neighbour to the sink as illustrated in Figure 25.

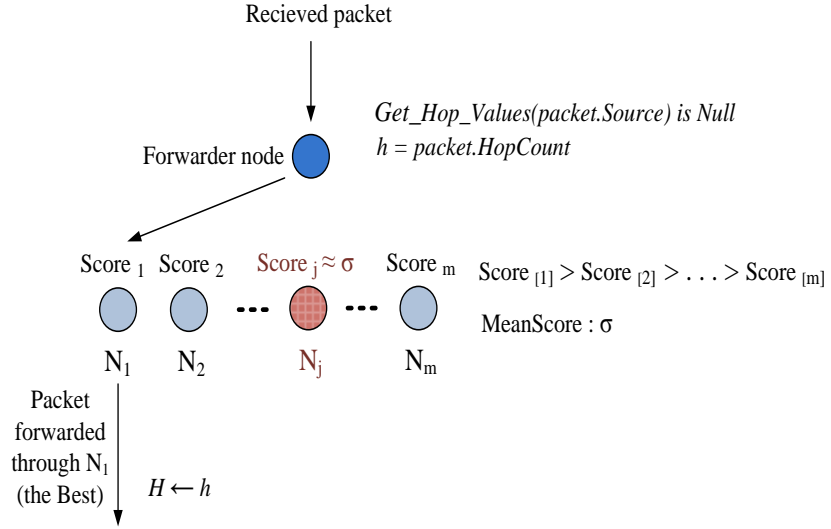


Figure 23: Forwarding the First Packet of a Data Stream.

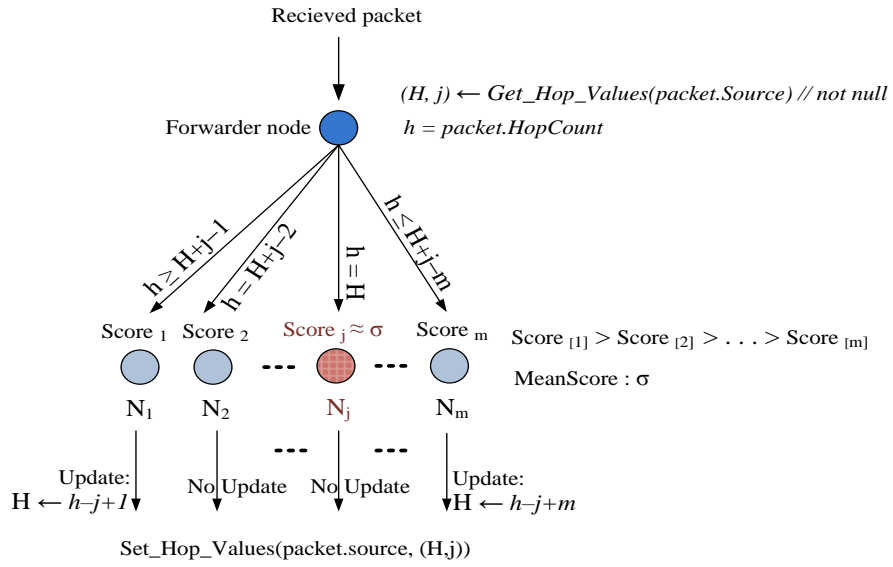


Figure 24: Forwarding a Packet of an already Known Data Stream.

In this case, the node enters the walking back forwarding mode in order to bypass this void. In such a case (see Figure 25), the forwarder node will inform all its neighbours that it cannot be considered as a neighbour to forward packets to the sink. This node will also delegate the forwarding responsibility to its nearest neighbour to bypass the void. This process does recursively step back until a node is found that can forward the packet successfully.

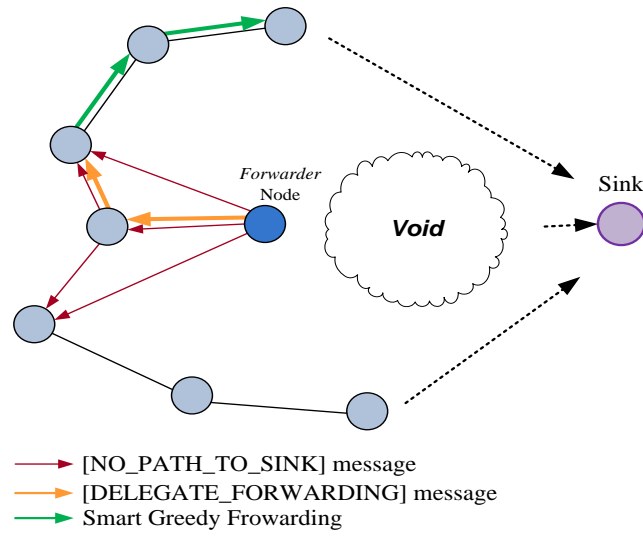


Figure 25: A Blocking Situation where a Node has no Forwarder Node.

This technique is better than the perimeter routing mode used in GPSR, since this kind of process is only done once a packet is received from an unknown stream, all the other packets belonging to the same stream will be routed avoiding the nodes that are facing a void toward the sink.

3.4 Performances Evaluation

3.4.1 Simulation Environment

We have considered a homogenous WMSN, in which, nodes are randomly deployed through the sensing field. The sensing field is a rectangular area of 500m x 200m. The sink node is situated at a fixed point in the righter edge of the sensing field at coordinates (490, 90) while a source node is placed in the other edge at coordinates (10, 90). We have considered this network for video surveillance (see Figure 26). In response to an event, the source node will send images with a rate of 1 image per second during 30 seconds. During transmissions, all neighbouring nodes consume hear the transmitted data packets and thus, nodes consume energy due to this radio communication behaviour..

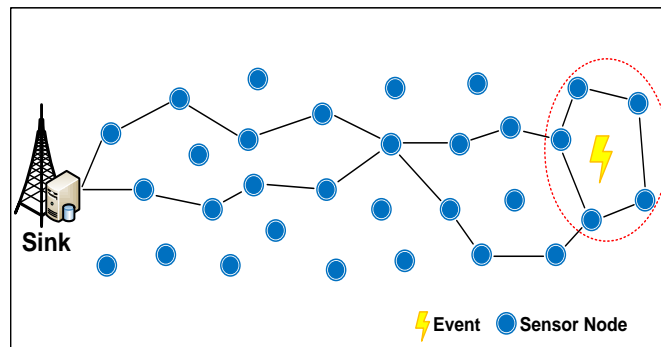


Figure 26: Data Delivery in Response to an Event in a WMSN.

To demonstrate and evaluate the performance of our proposed protocol AGEM, we used OMNeT++ 4 which is a discrete event network simulator [131]. To prove the effectiveness of AGEM, we have also implemented the GPSR algorithm (as an online but single-path routing protocol) and an adapted version of MPMPs on top of the TPGF algorithm (as an offline-multipath routing protocol) and we compared the simulation results. We have also introduced GEAMS (Greedy Energy-Aware Multipath Stream-based) [132] Routing protocol which consists of a “light” version of AGEM that does not include the adaptive compass mechanism for next hop node selection. Thus, GEAMS uses only distance-based greedy progression. Table 1 summarizes the simulation environment. We have considered that the link data is of type IEEE 802.15.4.

In all simulation scenarios, we assumed that all the nodes are aware of the geographic location of the sink node. Indeed, such information can be easily embedded into nodes' memory. However, if this is not possible other techniques can be used. Authors in [133], have proposed a distributed discovery mechanism in hybrid wireless networks.

Parameter	Value
Network Size	500m x 200m
Number of Sink Nodes	1
Number of Source Nodes	1
Number of Sensor Nodes	30, 50, 80
Number of Images	30 images
Image Size	10Kb
Image Rate	1 image/sec
Maximum Radio Range	80 meters

Table 1: Simulation Parameters (WMSNs).

To evaluate the performance of our protocol, we have considered the following three topology types:

3.4.1.1 Plain topology:

This topology is used to evaluate the behaviour of the routing algorithm especially the smart greedy forwarding mode.

Here, we have used three plain topologies; a network of 30, 50 and 80 sensor nodes. An example of these topologies is shown in Figure 27.

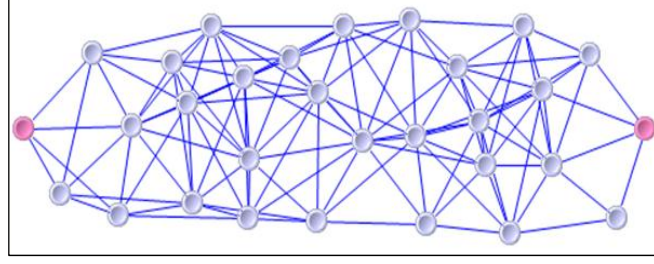


Figure 27: A 30-nodes network topology.

3.4.1.2 *Topology with holes:*

This topology is used to evaluate the performance of the routing algorithm in presence of holes (i.e. to evaluate the performance of the walking back forwarding mode).

We have used four topologies with holes; a network of 30 sensor nodes with one or two holes, and a network of 50 sensor nodes with one or two holes. An example of such topologies is shown in Figure 28.

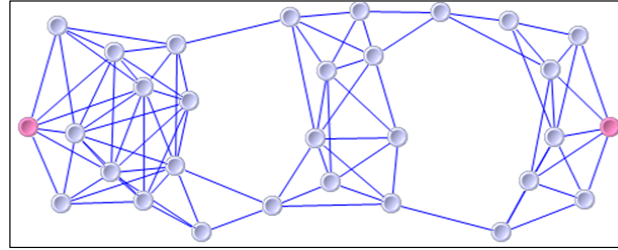


Figure 28: A 30-nodes network topology with two holes.

3.4.1.3 *Regular topology:*

This topology is used to evaluate the load-balancing feature of the algorithm. We have used one grid topology of 26 sensor nodes. This network is shown in Figure 29.

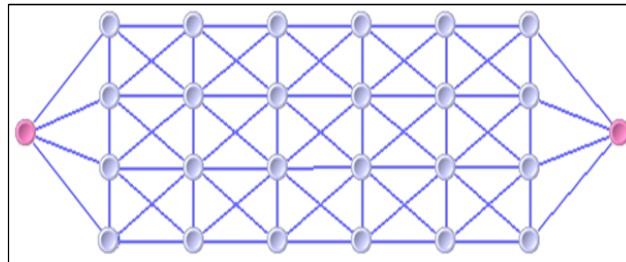


Figure 29: A 26-nodes grid network topology.

In all of the above topologies, we consider the minimum distance between two neighbouring nodes to be greater than 1 meter. For each topology, we have measured various metrics:

- *Global Energy Distribution (GED)*: it is the average and the standard-deviation of the residual energy at all network nodes.
- *Local Energy Distribution (LED)*: it is the average residual energy in contiguous regions of 40 meters width.
- *End-to-End Delay Distribution*: it is the average and the standard-deviation of the end-to-end delay.
- *Packet Loss Ratio*: it is the percentage of lost packets during the transmission.

3.4.2 Simulation Results:

In this section, we only present the simulation results obtained for different topologies using GPSR, TPGF, GEAMS and AGEM. The next section provides the discussion on the results obtained:

3.4.2.1 Plain topologies

The distribution of the residual energy in the network (GED) is shown in Figure 30.

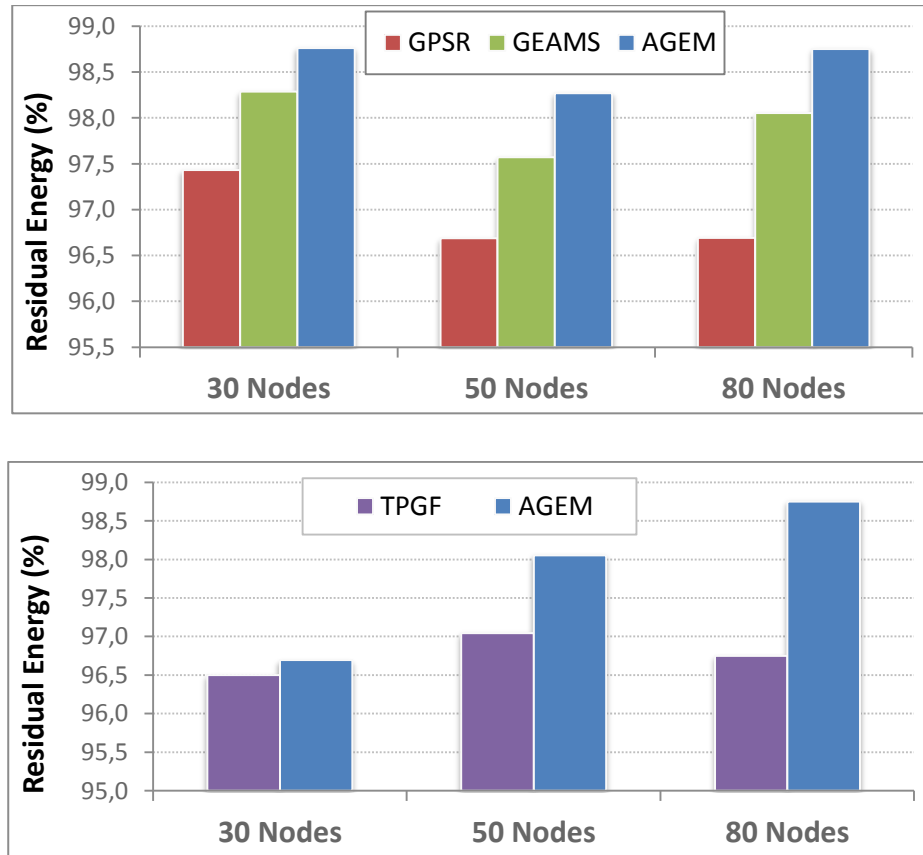


Figure 30: Average Residual Energy in “Plain” Topologies.

The distribution of the residual energy across the network (LED) is shown in figures Figure 31-Figure 32-Figure 33.

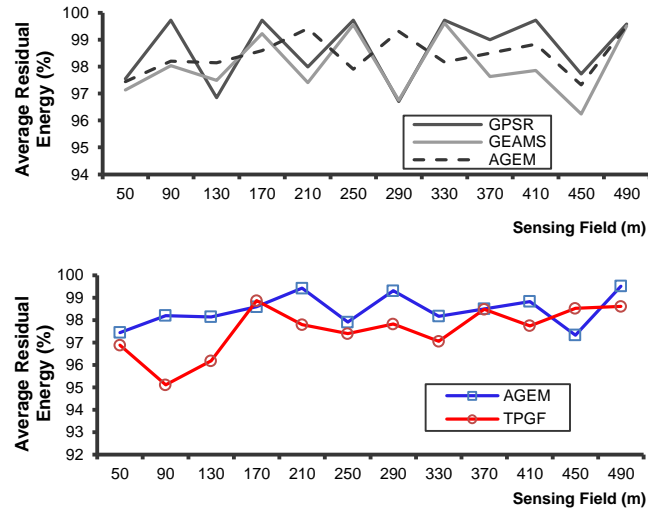


Figure 31: Residual Energy Distribution for 30-Node Network Topology

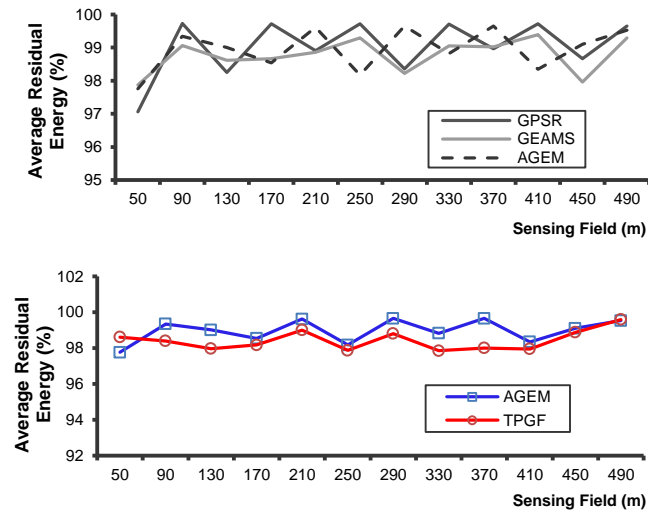


Figure 32: Residual Energy Distribution for 50-Node Network Topology.

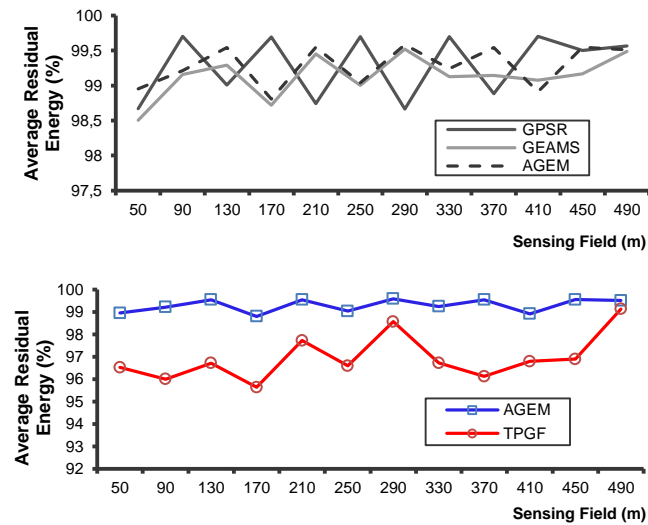


Figure 33: Residual Energy Distribution for 80-Nodes Topology.

The distribution of the end-to-end delay is shown in Figure 34.

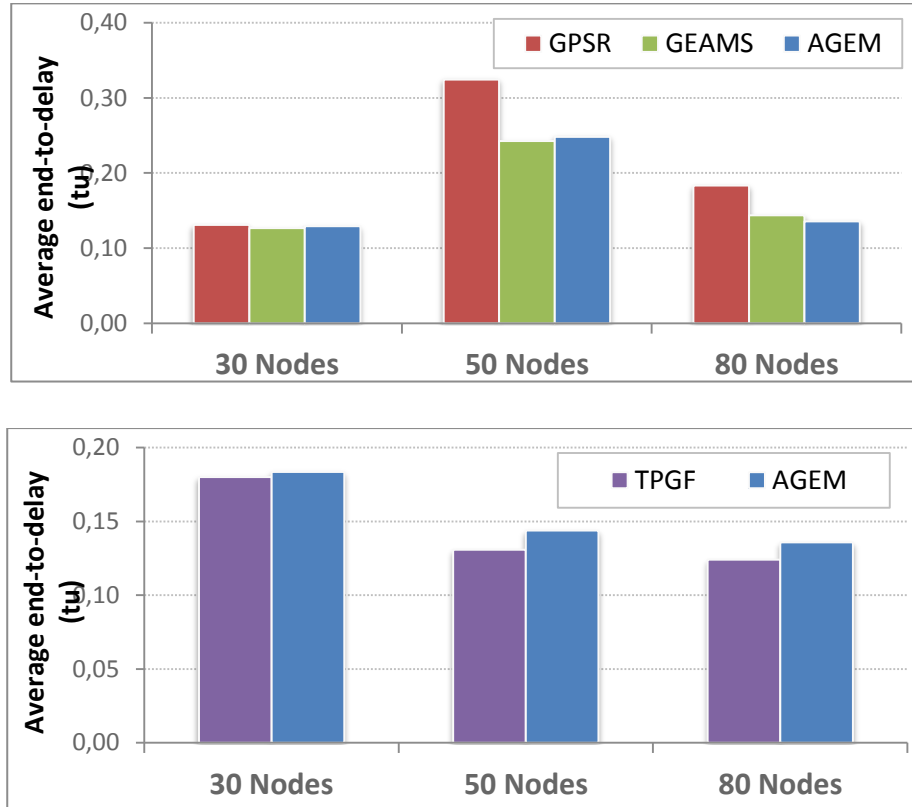


Figure 34: Average end-to-end delay in plain topologies.

The packets loss ratio during image transmission is shown in Figure 35.

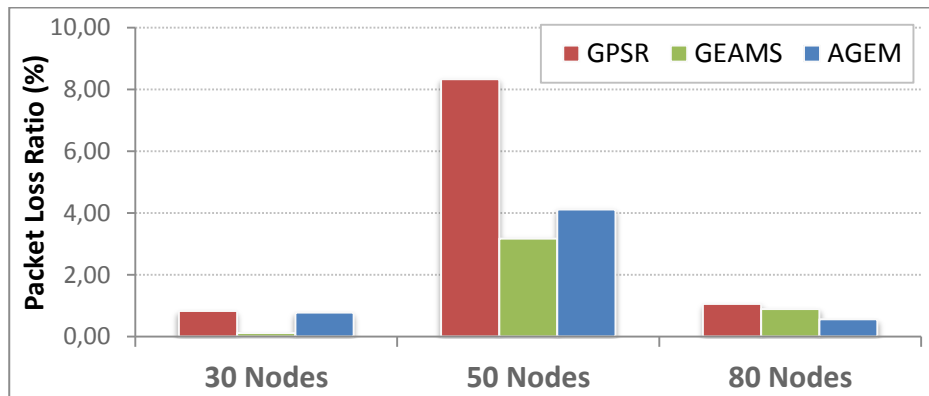


Figure 35: Packet-loss ratio in plain topologies.

3.4.2.2 Topologies with holes

The distribution of the residual energy in the network (GED) is shown in Figure 36.

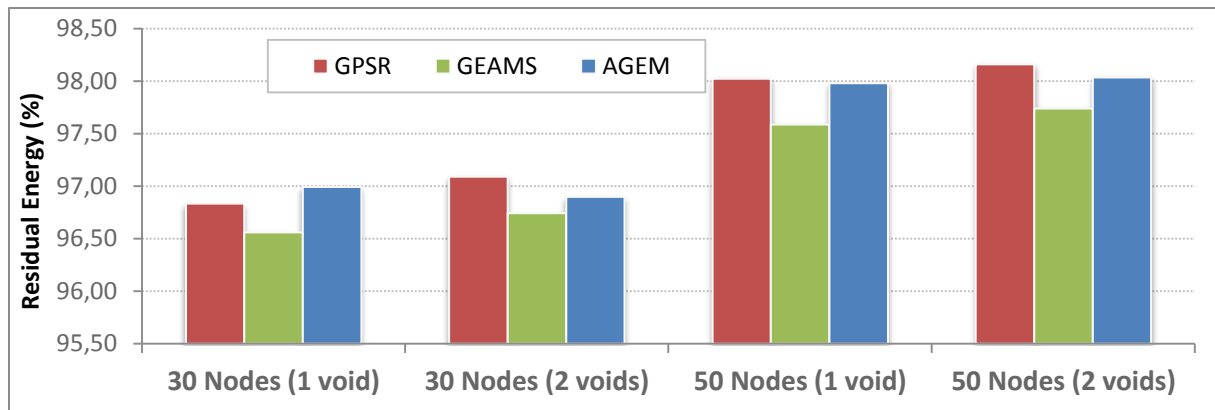


Figure 36: Average residual energy in topologies with holes.

The distribution of the residual energy across the network (LED) in a topology with holes is shown in Figure 37.

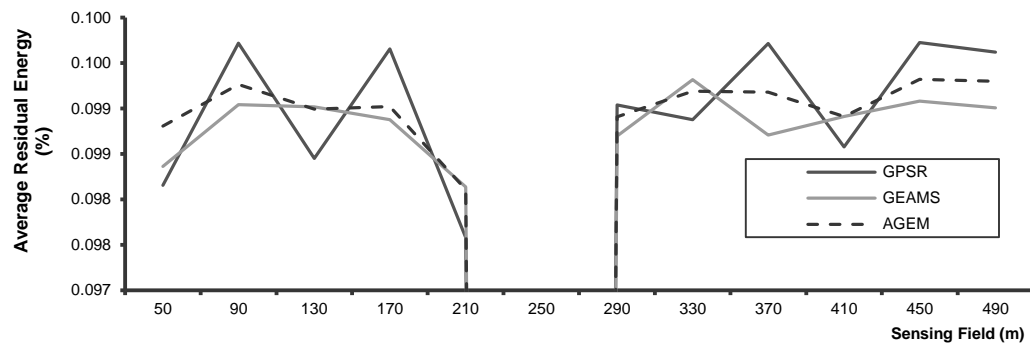


Figure 37: Residual Energy Distribution across the Network for 50-Node Network Topology with two holes.

(holes are in region 210m-290m along the sensing field)

The distribution of the E2E delay is shown in Figure 38.

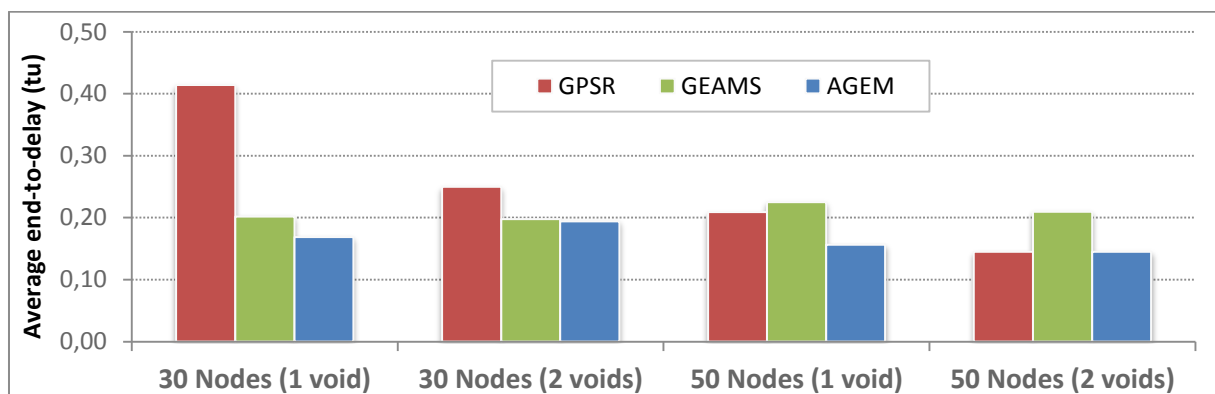


Figure 38: Average End-to-End Delay in Topologies with Holes.

The ratio of overall packet losses during the transmission is shown in Figure 39.

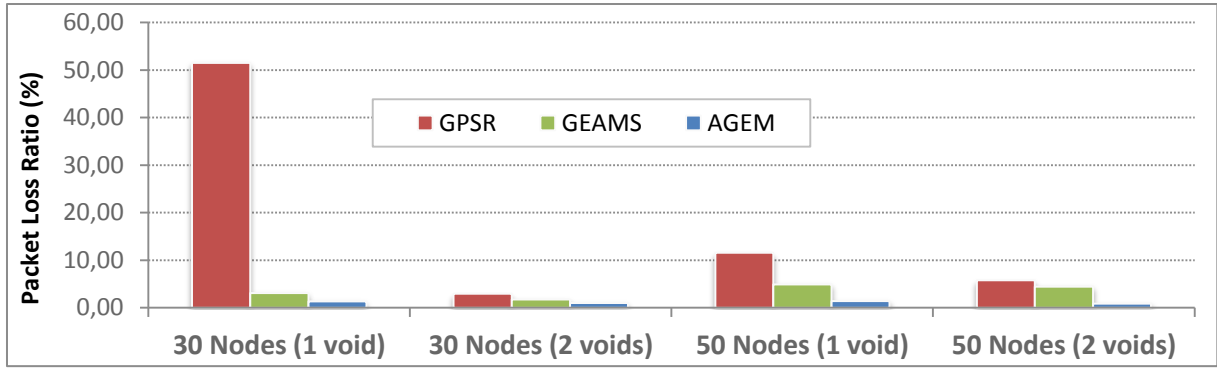


Figure 39: The Packet-loss Ratio in Topologies with Holes (Logarithmic Scale)

3.4.2.3 Regular topology

To illustrate the load-balancing feature of AGEM, we have used a grid topology and simulated a transmission between nodes *Src* and *Dest* as shown in Figure 40 (GPSR) and Figure 41 (AGEM). The figures show the residual energy at each node by the mean of a graduated colour that corresponds to their residual energy (Red to 0% and Blue to 100%).

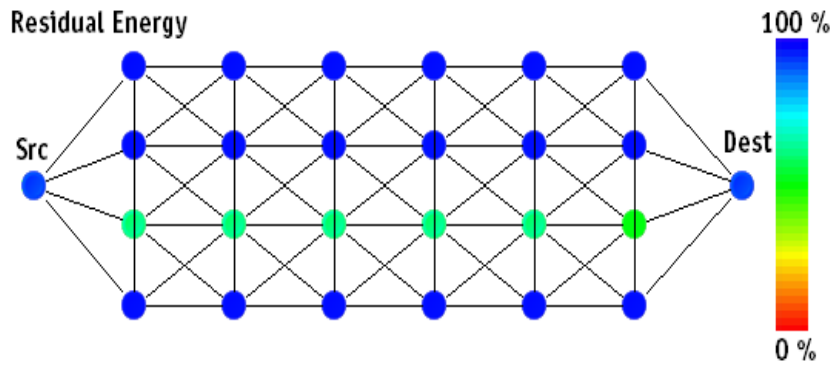


Figure 40: Residual Energy with GPSR in a Grid Topology.

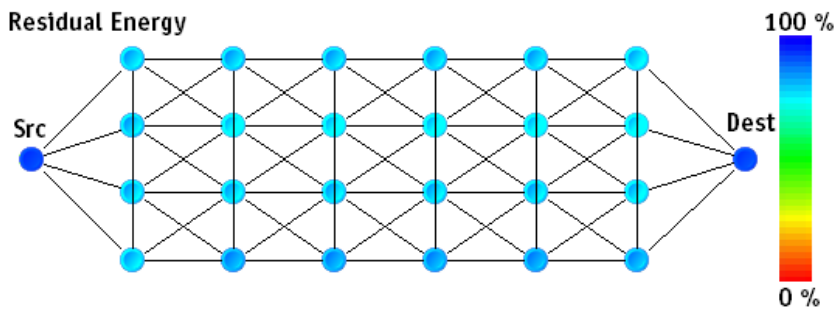


Figure 41: Residual Energy with AGEM in a Grid Topology.

3.4.3 Simulation Results Discussion

3.4.3.1 Global Energy Distribution (GED)

The GPSR protocol always uses the closest neighbour to the destination (see GPSR behaviour in a grid topology as shown in Figure 40) due to inflexible selection of the next hop

node. Forwarding packets to that neighbour is costly since the distance in a greedy forwarding is considered only and longer the distance is, the most energy consuming the transmission will be. This explains why residual energy in the case of GPSR is less than in the case of AGEM as shown in Figure 30 and Figure 36.

Although the use of multiple paths in TPGF, TPGF is still more energy consuming than AGEM since it uses “greedy” paths.

Moreover, the energy distribution in the network is well distributed with AGEM compared to GPSR. Unlike GPSR, AGEM use various nodes to perform online multipath routing and load balancing (see Figure 41).

3.4.3.2 *Local Energy Distribution (LED)*

Figures Figure 31, Figure 32, Figure 33, and Figure 37 illustrate the average residual energy of the network partitioned in regions of 40 meters width for the plain topologies and a topology of 50 nodes with two holes. We can clearly see that the energy is uniformly consumed through the network when using AGEM routing protocol compared to GPSR and TPGF routing protocols. Moreover, AGEM uses less energy than TPGF since TPGF is a greedy routing protocol and all the explored paths use always the greedy neighbour to forward packets. The benefit of such a feature is to prevent the network from being portioned into sub networks that are completely disconnected if some nodes die because of their energy depletion.

3.4.3.3 *Packet Loss and Transmission Delay*

By using multiple paths to transmit data packets, not only the packet transmission delay has been generally reduced first by using GEAMS and AGEM as shown in figures 20 and 26, but also, this end-to-end delay has become uniform as we can see by the mean of the standard-deviation as shown in Figure 34 and Figure 38.

However, this end-to-end delay remains quite bigger than the end-to-end delay while using an offline multipath routing protocol such as TPGF. This can be explained by the fact that TPGF uses totally disjoint paths to route packets. This makes packets safe from interference problems (retransmissions).

The packet loss ratio has also been decreased as shown in Figure 35 and Figure 39 in comparison with GPSR. The decrease in packet loss ratio and delay can be explained by the following points:

- The use of the same path will increase the queuing delays within nodes along the routes and causes network congestion.
- Sensor nodes have resources constraints, packet loss may occur due to the limited buffer sizes in sensor nodes.

In the case of topologies with holes, the perimeter routing mode employed by GPSR is not suited for burst transmissions which causes buffer over loads and packet losses.

These results demonstrate a better performance of AGEM to deliver multimedia traffic (still images in our simulation case) and provide better QoS compared to GPSR (lower the end-to-end delay and reduced packet loss ratio). AGEM is also more suitable to dense networks in which different paths to destination may exist.

3.5 Conclusion

In this chapter, we have described a new algorithm namely AGEM that is suitable for transmitting multimedia streaming over WMSNs. Because nodes are often densely deployed, different paths from source nodes to the base station may exist. To meet the multimedia transmission constraints and to maximize the network lifetime, AGEM exploits the online multipath capabilities of the WSN to achieve load balancing among nodes.

Unlike classic multipath routing protocols, AGEM routing protocol does not need overall network topology exploration and paths building before transmitting data packets. With AGEM forwarding decisions are made online as packets advance towards the destination node. Thus, control packets are reduced to the minimum.

Simulation results show that AGEM is well suited for WMSNs since it ensures uniform energy consumption and meets the delay and packet loss constraints.

Chapter 4

4 Predictive Routing in Mobile Wireless Networks

4.1 Introduction

Delay/Disruption Tolerant Network (DTN) may often refer to sparse mobile ad hoc network, where an end-to-end routing path does not necessarily exist. In DTNs, both nodes and links may be inherently unreliable. Due to these constraints, these networks are referred to as “*challenged networks*” [69][74]. Many other emerging communication networks fall into this paradigm. Vehicular ad hoc networks (VANETs), mobile sensor networks, and nomadic community networks are few examples.

An interesting DTN example is the city bus network, in which nodes consist of buses (cars, taxis, trams...) and communicate using short-range radios. With this type of networks, we can envision a lot of new applications: urban sensing, information dissemination (advertisement, traffic information, buses software update...) or even Internet access. Since this type of networks does not rely on an existing infrastructure, and they are formed in an ad-hoc fashion they may be an excellent solution for information dissemination in certain cases when there is no communication infrastructure or the existing one is down. Recently, revolution movements have gained some countries in North Africa. To counteract these protestation movements, government actors have shut down network infrastructures and disconnected the country from the internet in order to prevent people from accessing social networks. Many alternatives solutions have risen in the web. These propositions (such as the OpenMesh Project [134]) all agree to provide mechanisms to establish networks in ad-hoc fashion and to disseminate easily important information.

The proper functioning of such applications relies essentially on the efficiency of the routing task. However many challenges affect the routing in DTNs such as the changing network topology due to intermittent connectivity which is inherent to mobile networks as well as to static networks (in the case of low duty cycle of the nodes), and it results in low delivery ratio and high end-to-end delay. The problem of intermittent connectivity can be mitigated if the exact schedule or the dynamics of the network is known in advance. However, this is not often the case in DTNs as building this knowledge is an important issue. Thus, the efficiency of a DTN routing protocol relies essentially on the amount of network knowledge or “*oracles*” (information about contacts, queues or even data traffic) available to perform routing decisions.

Several routing protocols have been proposed for DTNs. These protocols differ by the amount of implemented *oracles*. Depending on the application, some oracles may not be used. For example, in a city bus network, it may not be possible to embed the entire schedule of contacts between buses in each node due to various reasons: (1) the memory space needed to store such information may be of huge size for a communicating node, (2) the “frozen” schedule may not reflect the actual networks dynamics since the schedule of a bus is not “certain”, (3) the exploitation of such information (for example, computing the best end-to-end route) can be highly computational costly. Then, the challenge in designing an efficient routing protocol for such networks is to make the communicating nodes smarter by using little information about the network and in a reliable distributed fashion.

In this chapter, we propose ORION [135], a routing protocol for mobile DTNs that capitalizes on the localization information of the nodes (geo-coordinates) and the nature of contacts between this type of nodes (buses, cars, taxis, trams) in an urban area. The contribution presented in this chapter is twofold. First, we have investigated deeply the inter-nodes encounter behaviour. Second, based on this behaviour analysis, we proposed ORION, a novel routing protocol that relies on predicting future contacts between nodes and greedy geographic forwarding of data packets. Thus, with ORION protocol, a communicating node will incrementally build knowledge about its network regarding the inter-nodes encounters behaviour and nodes positions. Thereby, it should be able to predict when it will be in contact with other nodes and for how long (duration). In this chapter, we have also investigated the requirements of ORION protocol in terms of computation and memory space for time series analysis and forecasting, and storage requirements for bundle carrying in the context of a store-and-forward routing protocol.

The remainder of this chapter is organized as follows. Section 4.2 presents a brief state of the art for DTN protocols and the use of stochastic processes and time series analysis in network communication modelling. Section 4.3 presents details of the proposed ORION protocol. In this section, we introduce the target application (subsection 4.3.1), and then we present our inter-nodes encounter behaviour analysis (subsection 4.3.2). Based on these analysis’ results, we define our routing protocol (subsections 4.3.3 and 4.3.4). Section 4.4 provides extensive simulation results and related discussion. Finally, section 4.5 concludes the chapter.

4.2 Related Work

In order to overcome the mentioned challenges in DTNs, it is important to design an efficient routing protocol that uses small network topology knowledge to maximize the delivery ratio and minimize the delay. Several routing protocols have been proposed for DTNs. These

protocols can be classified into two categories; replication-based and prediction (forwarding)-based protocols. With replication-based protocols, the contacts are assumed to be totally opportunistic and the required topology knowledge at each node is minimal. In this case, the simplest way to deliver a message is to send a copy to each encountered node. This is repeated until the destination receives the message. The Epidemic Routing protocol [66] envisions this strategy. With prediction-based protocols, only a single copy exists across the network at a given time. The protocol needs to be supplied with more knowledge about the network. Given the unavailability of topology information, some protocols try to use probabilities to predict the contact. However, such prediction can be at the price of reduced delivery ratio. Most of the existing prediction-based routing protocols focus mainly on whether two nodes would be in contact in the future, without paying much attention to “when” the contact will happen or “for how long” the contact will last. This lack of contact timing information degrades the contact prediction accuracy and negatively impacts the routing performance.

4.2.1 DTN Routing Protocols Taxonomy

As mentioned earlier, the replication-based routing strategy can achieve high delivery ratio while operating with minimal knowledge. This can be suitable for networks where contacts between nodes are unpredictable and random. However, this strategy is not optimal in terms of transmission and buffer size. It also suffers from the lack of scalability. Some protocols, adopting this strategy cope with this problem by bounding the number of copies in the network trading delay for buffer occupancy. To limit the replication, two solutions are used:

Fix the number of copies and spread them through distinct nodes. *Spray & Wait* routing protocol [80] uses this solution, also called *quota-based solution*.

Use metrics based on historical encounters between nodes to decide whether to send a copy or not. PROPHET [136] (Probabilistic Routing Protocol using History of Encounters and Transitivity) protocol uses this solution.

The PROPHET protocol utilizes an algorithm that makes use of the non-random aspect of the real world. This is done by maintaining a set of delivery success probabilities to known destinations, and by replicating messages during opportunistic contacts. Replication is done only for an encountered node which does not have a copy of the message and has a good probability to deliver the message to its final destination. Given a node i , the probability of node i to encounter another node j is denoted as $P(i,j)$. The delivery probabilities are computed during each contact driven by the following three rules:

- *Updating*: $P(M, E)_{\text{new}} = P(M, E)_{\text{old}} + (1 - P(M, E)_{\text{old}}) \times L_{\text{encounter}}$
where $L_{\text{encounter}}$ is an initializing constant.
- *Aging*: $P(i, j)_{\text{new}} = P(i, j)_{\text{old}} \times \gamma^n$
where γ is an aging constant and n is the number of time units elapsed since the last aging.
- *Transitivity*: $P(i, k)_{\text{new}} = P(i, k)_{\text{old}} + (1 - P(i, k)_{\text{old}}) \times P(i, j) \times P(j, k) \times \beta$
where β is a scaling constant.

In the prediction (forwarding) based protocols, a node is associated with a forwarding quality/probability metric for each destination, which is usually a direct (*one-hop*) forwarding quality such as contact frequency [136], or time elapsed since last contact [81][85][137].

During a contact, if a node i encounters another node j , node i will decide whether to send the message to node j based on the comparison between the direct forwarding qualities of node i and node j . The main drawback of this approach lies in the fact that good forwarding is not guaranteed due to these observations:

- Node j with a better forwarding quality than node i does not necessary mean that node j is a good forwarder.
- Despite the good quality of node j , node i may encounter better nodes in the near future.

Similarly, even though the forwarding quality of node j is lower than node i , node j may be still the best forwarder that node i could encounter in the future.

4.2.2 Times Series in Network Modelling

The proposed ORION protocol makes use of time series to predict contacts. A time series is an ordered sequence of values of a variable $\{y_t\}_{t \in T}$ indexed by an ordered set $= \{t_1, t_2, t_3, \dots, t_n\}$. The time series analysis serves two purposes: (1) Obtain an understanding of the underlying forces and structure that have produced the observed data, and (2) Fit a model and proceed to forecasting, monitoring or even feedback and feedforward control. Time series analysis is used for many applications such as economic forecasting, sales forecasting, budgetary analysis, stock market analysis, yield projections, process and quality control, etc. Recently, it starts being used in the field of computer networks communications. Indeed, time series have gained the attention of many researchers for the modelling of the Internet and wireless mobile networks traffic. In [138], Basu *et. al.* have modelled the Internet traffic using Auto Regressive Moving Average (ARMA) process of order (p, q) . Using this model, they predict the traffic generated by a TCP source using FDDI protocol. In [139], Liu *et. al.* have proposed an energy efficient technique for data collection in Wireless Sensor Networks. A sensor is hold from transmitting redundant data. The data are not

sent if they can be predicted by the sink node. For prediction, they utilize Auto Regressive Integrated Moving Average (ARIMA) model of order (p,d,q) [140] due to its outstanding model fit and small computational cost. In [141], Herbert *et. al.* extend this idea to the hierarchic routing protocol LEACH [142] by providing verification at the cluster head. This approach has shown great communication cost savings. In [143], Banerjee *et. al.* used a *birth and death* process to model the network's dynamics. A node entering in the transmission range of a source node is considered as a *birth*. Similarly, a *death* refers to when it leaves this range. Finally, in [144], Singh *et. al.* extend this idea by using an AutoRegressive (AR) process to model the number of a node's neighbours in a mobile ad hoc network.

When dealing with stochastic processes, values of the involved random variables are taken over time forming the time series for further analysis. An important step while analysing time series is to determine the suitable model (or class of models) fitting the observed data. A common approach to analyse time series is the use of *ARMA* analysis. An *ARMA* process is a combination of an Autoregressive process (*AR*) and a Moving Average (*MA*) process. In an *AR* process, a random variable is “explained” by its past values rather than other variables. While with *MA* process, a random variable is supposed to be explained by its actual mean, augmented by a weighted sum of the errors (random shocks) that tainted the previous values. *ARMA* analysis was introduced by Box and Jenkins [145] and they have identified three steps to model and forecast time series:

- *Model Identification*: this step is performed to estimate a model structure by using two essential functions: the autocorrelation function (ACF) and the partial autocorrelation function (PACF).
- *Parameter Estimation*: this step is performed for fitting the identified model to the observed data. This is achieved by determining the coefficients of the linear combination.
- *Forecasting*: the final objective is to predict the future values of the time series based on the already observed data and the linear combination estimated at the second step.

And so, *ARMA*(p,q) model is defined as: $y_t = c + \mu + \sum_{i=1}^p \varphi_i y_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + e_t$

$$y_t = c + \mu + \sum_{i=1}^p \varphi_i y_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + e_t \quad (Eq.1)$$

where:

- p, q Non-negative integers, orders of the AR and MA processes respectively,
- φ_i, θ_j Time-invariant coefficients of the AR and MA models respectively,

- μ Expectation of y (often assumed to be equal to zero) and c a constant (often omitted),
- e_t Samples of white noise with mean zero and variance σ^2 and ε_t the white noise error terms.

To be considered for ARMA analysis, a time series must be stationary. To verify the stationnarity two conditions must hold:

$$E(y_t) = \mu \text{ is constant independent of instant } t \quad (Eq.2)$$

$$Cov(y_t, y_{t-j}) = \gamma^j \text{ only depends on time lag } j. \quad (Eq.3)$$

4.3 ORION Routing Protocol

4.3.1 Target Application

In this paper, we have considered a city-bus network in which the communicating nodes consist of buses, trams, cars and hotspots. The buses and trams are assumed to be “*regular*” mobile nodes, where the cars are assumed to be “*random*” mobile nodes and finally the hotspots and access points to be fixed nodes. The regular nodes move across the area along a certain trajectory, while random nodes move freely across the urban area. In this scenario, all mobile nodes move with a non-constant speed. Each communicating node is assumed to be equipped with localization hardware. Consequently, we propose to utilize geographic addressing and achieve data packets forwarding in a greedy fashion based on distance and/or angle calculus. With geographic Routing/Greedy Forwarding, the network address of each node includes geographic coordinates (for example a node [A], at (x,y) will have the address ID-A.X.Y). Forwarding is then said greedy if we use the geographic information for choosing forwarder nodes (e.g., choosing the closest neighbour from the destination node as the next hop).

Following the Box and Jenkins steps to model the times series using ARMA model, we have conducted some simulations of our city-bus network. In these simulations, instead of using synthetic mobility models [146][147][148], we studied the two time series in pseudo-realistic environment mapped on a real city map, namely *Bordeaux* in *France*. In this scenario, nodes that represent bus or trams are moving across the different routes with constant speed between each two stations. Nodes that represent cars or people are moving freely with constant speed.

ORION is based on greedy geographic forwarding and contact prediction. In the following, we explain our methodology to achieve an efficient contact prediction.

4.3.2 Contact Behaviour Analysis

For our analysis and in order to use efficiently time series, we propose to discrete the time into small periods of time Δt . In the description, Δt we further denote $(1\Delta t, 2\Delta t, \dots, n\Delta t)$ as the time instants (t_1, t_2, \dots, t_n) .

In networks with intermittent connectivity, a node becomes aware of an eventual contact by the mean of periodically exchanged *HELLO* messages. Consequently, contact (connection) duration C with a certain node is the sum of consecutive periods of time Δt over which the node received at least one *HELLO* message from the other node. Respectively, the duration of the non-contact (disconnection) \bar{C} is the sum of consecutive periods of time Δt over which the node did not receive any *HELLO* messages from the other node. The duration of a contact C and a non-contact \bar{C} are two random variables.

In order to study the contact behaviour and based on the consecutive values of the two random variables C and \bar{C} , we construct the two times series $\{C_t\}_{t \in N}$ and $\{\bar{C}_t\}_{t \in N}$, where C_i denotes the duration of the i^{th} contact (connection), and \bar{C}_i represents the duration of the i^{th} non-contact (disconnection). N is the set of natural integers.

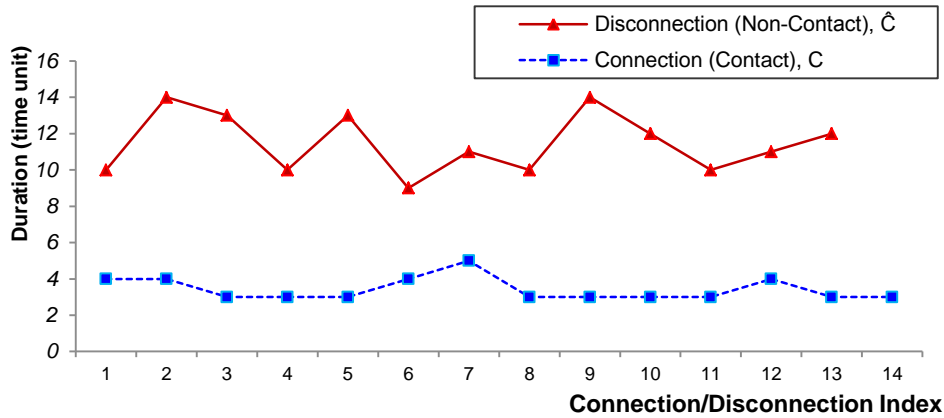


Figure 42: Variation of C_i and \bar{C}_i over time.

Examples of $\{C_t\}_{t \in N}$ and $\{\bar{C}_t\}_{t \in N}$ chronograms are shown in Figure 42. To apply the Box-and-Jenkins approach, we had to verify the stationnarity of the two time series. Thus, we run the stationnarity test (see Eq.2 and Eq.3). The results showed that the two stationnarity conditions hold for almost all the time series obtained from the simulation (at the rate of two times series C_i and \bar{C}_i by contacted node at each node). Consequently, C_i and \bar{C}_i can be analysed using ARMA.

Based on this information, a node can predict the future value of the contact's duration (connection's duration), and also the future value of the non-contact duration (disconnections'

duration). Consequently, the node will be able to predict when the next contact will be and for how long it will last. This knowledge will be extremely beneficial to perform routing decisions.

4.3.3 ORION Contact Model Construction

After running the simulation, we extracted two time series, namely the $\{C_t\}_{t \in N}$ and $\{\bar{C}_t\}_{t \in N}$, for each frequently contacted node. It was interesting to notice that all the time series were quite similar in terms of pace, even if the mobiles nodes were moving with different non-constant speeds.

The rest of this section describes the Box and Jenkins steps applied to model the proposed times series. We dubbed this model as “*ORION Contact Model*” as it is related to the targeted application scenario.

4.3.3.1 Step 1: ORION Contact Model Identification

We have used Minitab [149] to analyse the obtained time series. The autocorrelation function (ACF) and the partial autocorrelation function (PACF) are plotted in Figure 43 and Figure 44.

According to the *ACF* and *PACF* plots, the results indicate that the best fitting model is the *ARMA(2,1)* since *PACF* presents two significant peaks (i.e. this confirms the *AR(2)* part), and the *ACF* presents one significant peak (i.e. this confirms the *MA(1)* part).

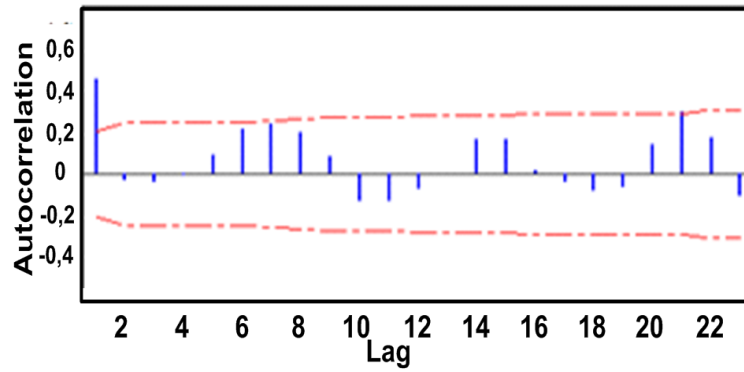


Figure 43: Autocorrelation Function (ACF) plot for contact's duration.

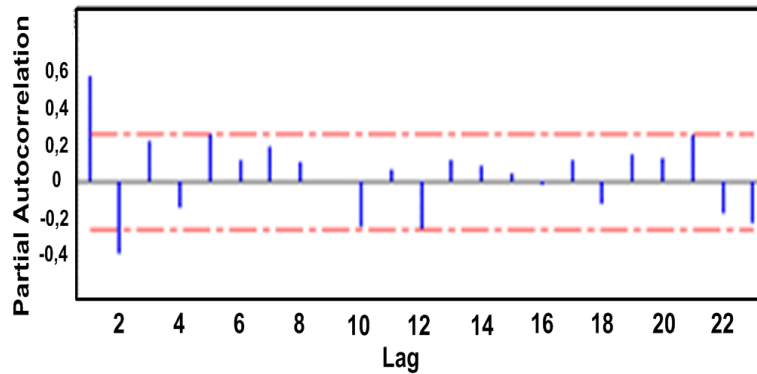


Figure 44: Partial Autocorrelation Function (PACF) plot for contact's duration.

Based on these results, the ORION Contact Model obtained can be written as:

$$C_i = \mu + \varphi_1 C_{i-1} + \varphi_2 C_{i-2} + \theta_1 \varepsilon_{i-1} + \varepsilon_i \quad (Eq.4)$$

where:

μ denotes the mean value of C_i

$\varphi_1, \varphi_2, \theta_1$ denote the ORION Contact Model parameters (φ_1, φ_2 related to the autoregressive part and θ_1 related to the moving average part).

$\varepsilon_i, \varepsilon_{i-1}$ are assumed to be independent, identically distributed random variables sampled from a normal distribution with zero mean $\varepsilon_i \sim N(0, \sigma^2)$ where σ^2 is the variance.

4.3.3.2 Step 2: ORION Contact Model Parameters Estimation

The second step after identifying the order of the ORION Model is to estimate its parameters. For the *AR* part, the parameters can be obtained by the Yule-Walker equations [150]. The principle of the Yule-Walker equation relies on the fact that there is a direct correspondence between the parameters ($\varphi_i; i = 1, \dots, p$) and the covariance function of the process. This correspondence can be inverted to determine the parameters from the *ACF* which leads to the Yule-Walker equations:

$$\gamma_m = \sum_{k=1}^p \varphi_k \gamma_{m-k} + \sigma_\varepsilon^2 \delta_m \quad (Eq.5)$$

where $m = 0, \dots, p$ yielding $(p + 1)$ equations. γ_m is the autocorrelation of Y . σ_ε is the standard-deviation of the input noise process, and the δ_m is the *Kronecker Delta* function. This equation is usually solved by representing it as a matrix, getting the following equation solving all φ .

$$\begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} \gamma_0 & \gamma_{-1} & \gamma_{-2} & \dots \\ \gamma_1 & \gamma_0 & \gamma_{-1} & \dots \\ \gamma_2 & \gamma_1 & \gamma_0 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \vdots \end{bmatrix} \quad (Eq.6)$$

This equation provides a way to estimate the *AR*(p) parameters by replacing the theoretical covariance with estimated values. For the *MA* part, the single parameter is obtained by identification based on the estimated *AR* parameters and the last estimation error.

4.3.3.3 Step 3: Forecasting

Since the orders of the ORION Model are fixed in time due to the mobility model, the computational cost of resolving linear systems can be avoided by extracting generic formulas. The

node will have to compute the model parameters based on simplified mathematical expressions. Moreover, since these formulas include only aggregated data (sums, means, standard-deviations, variances ...), there is no need to store all the past data; only few values are maintained at each node. The following sub-section explains the different steps to derive these simplified mathematical expressions and how they will be used for forecasting. Since the model is ARMA(2,1), it is composed of two parts: AR(2) and MA(1).

For AR(2) process we have :	$x_{t+1} = \varphi_1 x_t + \varphi_2 x_{t-1} + \xi_{t+1}$
We multiply both sides by one lag value and take the expectation:	$\langle x_t x_{t+1} \rangle = \varphi_1 \langle x_t x_t \rangle + \varphi_2 \langle x_t x_{t-1} \rangle + \langle x_t \xi_{t+1} \rangle$
We eliminate the zero correlation forcing term ($\langle x_t \xi_{t+1} \rangle$) and we divide by $N-1$:	$\frac{\langle x_t x_{t+1} \rangle}{N-1} = \varphi_1 \frac{\langle x_t x_t \rangle}{N-1} + \varphi_2 \frac{\langle x_t x_{t-1} \rangle}{N-1}$
We then have:	$c_1 = \varphi_1 c_0 + \varphi_2 c_1$ (c_i is the covariance or lag i)
We divide both sides by c_0 , we obtain the equation :	$r_1 = \varphi_1 r_0 + \varphi_2 r_1$ since $r_i = c_i / c_0$
Doing the same thing with lag2, we find the second equation. Then we have :	$\begin{cases} r_1 = \varphi_1 r_0 + \varphi_2 r_1 \\ r_2 = \varphi_1 r_1 + \varphi_2 r_0 \end{cases}$
Leading to the Yule-Walker equations:	$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \underbrace{\begin{pmatrix} r_0 & r_1 \\ r_1 & r_0 \end{pmatrix}}_R \underbrace{\begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}}_\Phi$, and so $\Phi = R^{-1}r$
Knowing that $r_0 = 1$:	$\begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix} = \frac{1}{1-r_1^2} \begin{pmatrix} 1 & -r_1 \\ -r_1 & 1 \end{pmatrix} \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}$
Finally, we get :	$\varphi_1 = \frac{r_1(1-r_2)}{1-r_1^2}$ and $\varphi_2 = \frac{r_2-r_1^2}{1-r_1^2}$
Considering the MA(1) process:	$x_t = \theta \xi_{t-1} + \xi_t$ (where ξ is the white noise $N(0, \sigma^2)$)
We multiply both sides by one lag value and take the expectation:	$x_{t-1} x_t = (\theta \xi_{t-2} + \xi_{t-1})(\theta \xi_{t-1} + \xi_t)$ $\langle x_{t-1} x_t \rangle = \langle \theta^2 \xi_{t-2} \xi_{t-1} \rangle + \langle \theta \xi_{t-2} \xi_t \rangle + \langle \theta \xi_{t-1}^2 \rangle + \langle \xi_{t-1} \xi_t \rangle$
We eliminate the zero terms and we divide by $N-1$:	$\frac{\langle x_{t-1} x_t \rangle}{N-1} = \frac{\langle \theta \xi_{t-1}^2 \rangle}{N-1}$ (knowing that $\frac{\langle \xi_i \xi_j \rangle}{N-1} = \begin{cases} 0 & \text{if } i \neq j \\ \sigma^2 & \text{if } i = j \end{cases}$)
And we get :	$c_1 = \theta \sigma^2$
By repeating the same operations for zero lag value :	$x_t x_t = (\theta \xi_{t-1} + \xi_t)(\theta \xi_{t-1} + \xi_t)$
We obtain :	$c_0 = \theta^2 \sigma^2 + \sigma^2 \rightarrow c_0 = \sigma^2 (1 + \theta^2)$

Knowing that, and from the two obtained equations we have :

$$r_1 = \frac{c_1}{c_0} = \frac{\theta}{1 + \theta^2}$$

By solving the quadratic equation we find :

$$\theta = \frac{1}{2r_1} \pm \sqrt{1 - 2r_1^2}$$

From the three boxed formulas, we can see that the estimation of ORION Contact Model parameters relies on the estimated values of autocorrelation of order 1 and 2. (i.e. r_1 and r_2). Statistically, autocorrelation of order p (i.e. r_p) is estimated by the following expression:

$$r_p \cong \frac{E[(X_t - \mu)(X_{t-p} - \mu)]}{\text{Var}(X_t)} \cong \frac{E[(X_t - \mu)(X_{t-p} - \mu)]}{E[X^2] - E[X]^2}$$

where:

$$E_X = E[X] = \mu = \frac{1}{N-1} \sum_{i=1}^N x_{t-i+1};$$

$$E_{X^2} = E[X^2] = \frac{1}{N-1} \sum_{i=1}^N x_{t-i+1}^2;$$

$$E_{X, X_p} = E[(X_t - \mu)(X_{t-p} - \mu)] = \frac{1}{N-1} \sum_{i=1}^N (x_t - \mu)(x_{t-p} - \mu);$$

We can see that the calculus of the autocorrelation terms relies on aggregated terms (averages). Thus, these values can be incrementally computed without keeping the entire data set as follows:

$$E_{X_{(t)}} = \frac{((N-1)E_{X_{(t-1)}} + x_t)}{N}$$

$$E_{X^2_{(t)}} = \frac{((N-1)E_{X^2_{(t-1)}} + x_t^2)}{N}$$

$$E_{X, X_{p(t)}} = \frac{((N-1)E_{X, X_{p(t-1)}} + (x_t - \mu)(x_{t-p} - \mu))}{N}$$

Finally, in order to adaptively estimate the parameters of the $ARMA(2,1)$ process and in real-time, we only need to store the following 7 variables (rather than the entire time series):

- N The number of the considered values so far $[0, t)$
- x_t, x_{t-1}, x_{t-2} The last three values of the time series.
- E_X The last average of the values (at $t-1$)
- E_{X^2} The last average of the squared values (at $t-1$)

— E_{X,X_1} , E_{X,X_2} The last values of E_{X,X_1} and E_{X,X_2} respectively

Since the data are evolving in time, we propose to compute these parameters in an incremental fashion. For two different instants $t_1 < t_2$ the estimated parameters are different because the estimation at t_1 takes into account the data up to t_1 (i.e. $[0, t_1]$) and similarly the estimation at t_2 takes into account all the data in $[0, t_2]$. This approach makes the estimation in real-time and more accurate with new observed data. The process of model parameters' update and future value forecasting is explained with the pseudo code in Figure 45.

<i>On_New_Value(v)</i>	
010:	$N++;$
020:	$\text{Update_Sliding_Window}(v, x_t, x_{t-1}, x_{t-2});$
030:	$E_X = \text{Compute_New_Average}(E_X, N, x_t);$
040:	$E_{X^2} = \text{Compute_New_Average}(E_{X^2}, N, x_t);$
050:	$E_{X,X_1} = \text{Compute_New_Average}(E_{X,X_1}, N, x_t, x_{t-1});$
060:	$E_{X,X_2} = \text{Compute_New_Average}(E_{X,X_2}, N, x_t, x_{t-2});$
070:	$r_1 = \text{Compute_AutoCorrelation}(E_X, E_{X^2}, E_{X,X_1});$
080:	$r_2 = \text{Compute_AutoCorrelation}(E_X, E_{X^2}, E_{X,X_2});$
090:	$\phi_1 = \text{Compute_Phi1}(r_1, r_2);$
100:	$\phi_2 = \text{Compute_Phi2}(r_1, r_2);$
110:	$\theta = \text{Compute_Theta}(r_1);$
120:	$x_{t+1} = \text{Estimate_Future_Value_ARMA_2_1}(\phi_1, \phi_2, \theta);$

Figure 45: Online model parameters update, and future value forecasting

Figure 46 presents a comparison between forecasting based on “*offline*” parameters estimation (i.e. the parameters are estimated considering the entire data set, then the future values are computed at each index using the obtained model) and forecasting based on “*online*” estimation (i.e. the parameters are estimated for each new observation, considering the available data so far). We can clearly see that our online estimation is better than the offline estimation in predicting the actual data.

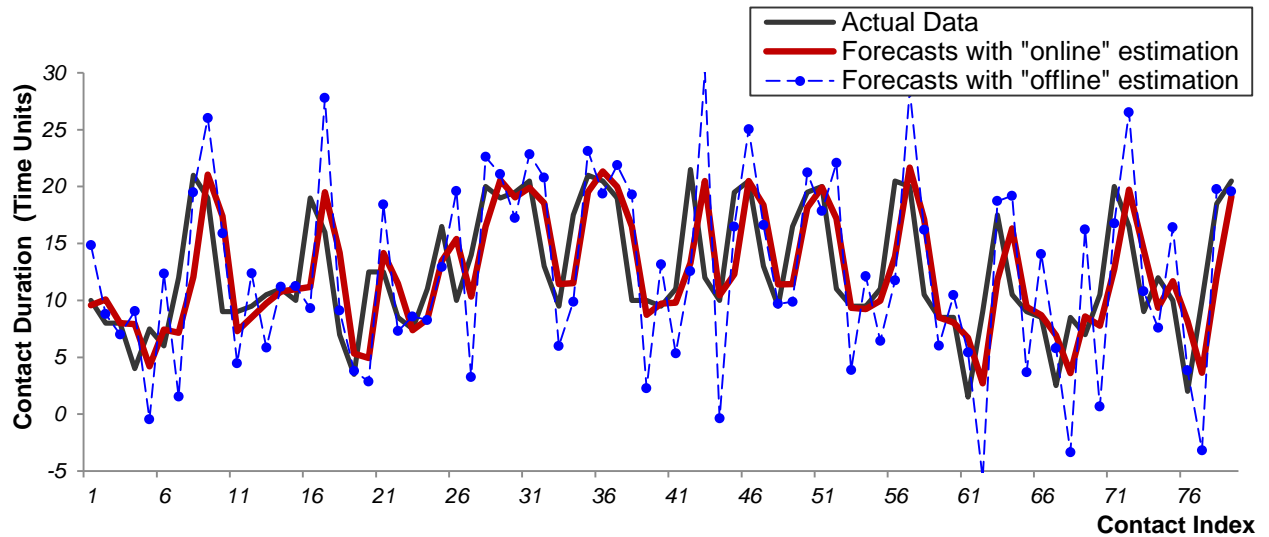


Figure 46: Forecasting with "online" and "offline" parameter estimation.

4.3.4 Forwarding Algorithm

The forwarding algorithm used in ORION is based on three criteria: (1) in order to forward a packet in a greedy manner, a node will look for the closest connected neighbour to the destination, (2) if such a node is not available, the forwarder node will look for the most advancing connected neighbour toward the destination, and finally (3) if there is no such a node, the forwarder node will schedule the data packet for the best future connected neighbour. A pseudo code of the algorithm is shown in Figure 47. A detailed version is shown in Figure 48.

<i>On_Forwarding_Packet</i>	
10:	nextHop \leftarrow Closest Connected Neighbour to the Destination;
20:	IF (nextHop \neq null) GOTO 80;
30:	nextHop \leftarrow Most Advancing Connected Neighbour towards the Destination;
40:	IF (nextHop \neq null) GOTO 80;
50:	nextHop \leftarrow Best Future Connected Neighbour;
60:	IF (nextHop \neq null) GOTO 90;
70:	Store_Packet(); END.
80:	Send_Packet_To(nextHop); END.
90:	Schedule_Packet_For(nextHop); END.

Figure 47: Pseudo code for ORION forwarding algorithm.

Forward_Packets (*pk*)

Packet_Queue: a data structure where all the packets to be sent is stored.

Connected_Neighbors_Set (CN): the set of all neighbours that are currently in contact with this node.

Estimated_Neighbors_Set (EN): the set of all estimated neighbours, i.e. the nodes whose contacts we have a historical data about.

Forwarder_Node (FN): the address of the next hop.

f_{opt} : This function gives a score to a neighbour based on its next contact date. This function can be configured to give priority to delivery speed or delivery certainty, or both of the two criteria.

```
01:  if (Packet_Queue is not Empty) {
02:      pk = Packet_Queue.pop();
03:      if (pk.Next_Hop == null) { //packet was not scheduled
04:           $FN = \argMin \|\vec{N_{pos}pk_{dest\_pos}}\|; N \in CN$ 
05:          if (FN  $\neq$  null)
06:              send_packet(pk, FN);
07:          else { // Most advancing neighbour towards the destination
08:               $FN = \argMax (\|\vec{N_{new\_pos}pk_{dest\_pos}}\| - \|\vec{N_{old\_pos}pk_{dest\_pos}}\|); N \in CN$ 
09:              if (FN  $\neq$  null)
10:                  send_packet(pk, FN);
11:              else { //best future contact
12:                   $FN = \argMax f_{opt}(N_{next\_contact\_date}); N \in EN$ 
13:                  pk.Next_Hop = FN;
14:                  Packet_Queue.push(pk);
15:              }
16:          }
17:      }
18:      else { //packet was scheduled for a certain node
19:          if (pk.Next_Hop  $\in$  CN) { // is the predicted neighbour connected?!
20:               $FN = \argMin \|\vec{N_{pos}pk_{dest\_pos}}\|; N \in CN$ 
21:              send_packet(pk, FN);
22:          }
23:          else { // the predicted neighbour is not connected
24:              pk.Next_Hop = null; // unscheduling the packet
25:              Packet_Queue.push_back(pk); // storing the packet
26:              Forward_Packets(); // Starting Over
27:          }
28:      }
29:  }
```

Figure 48: A detailed description of the ORION forwarding algorithm.

4.4 Performances Evaluation

4.4.1 Simulation Environment

For simulation purpose, we have considered a homogenous wireless mobile network in which nodes are randomly deployed through an area of 1000m x 1000m. Two nodes are selected randomly at the beginning of the simulation to act as source and destination. The source sends periodically data packets to the destination. The simulation is run for 1800 seconds (letting sufficient start-up time for PROPHET, i.e. 600 seconds). To demonstrate and evaluate the performance of ORION, we used OMNeT++ 4.0 [131]. As a comparison term, we use the PROPHET protocol. We considered variant network topologies by varying (1) the number of nodes (i.e., 30, 50, and 70 nodes) and (2) the nodes speed (i.e., 5 m/s, 10 m/s, 15 m/s and 20 m/s). For each topology, we measured various parameters: (1) the average hop count from the source to the destination, (2) the packets delivery ratio, (3) the first packet arrival, and finally (4) the average end-to-end delay. To avoid redundancy, results relative to the 50 nodes topology are not shown since they are similar to those of the 70 nodes topology.

We also prove that ORION routing protocol does not require more space memory to perform store-carry-and-forward routing by measuring the message queue occupancy during all the simulation period.

4.4.2 Simulation Results Discussion

4.4.2.1 Hop Count (HC)

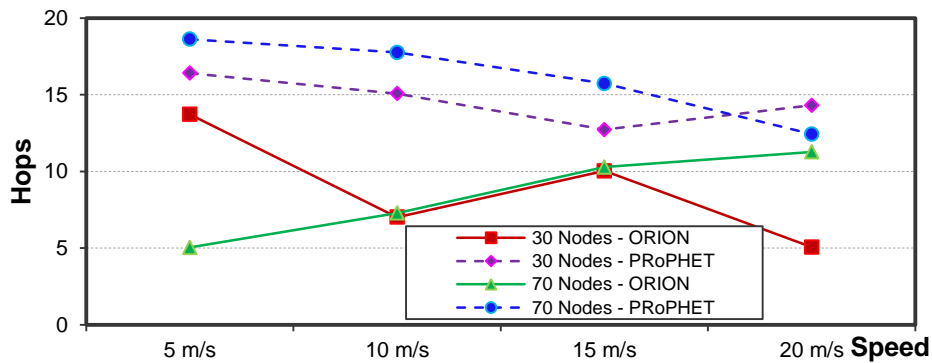


Figure 49: Average hop count in 30 and 70 nodes topologies with variant speed.

From Figure 49, we can clearly see that ORION delivers packets along fewer hops than PROPHET and this is the case for all the three topologies and with all nodes speeds. This is achieved thanks to the twofold forwarding strategies of ORION protocol (store-and-forward and store-carry-and-forward) while PROPHET is just a store-and-forward protocol.

4.4.2.2 Packet Success Ratio (PSR):

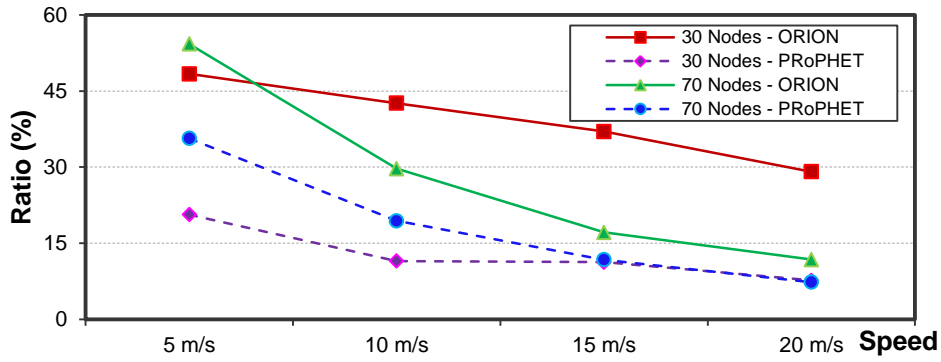


Figure 50: Packet Success Ratio in 30 and 70 nodes topologies with variant speed.

Since the selection of the next forwarder node in ORION is based on three criteria (i.e. closest neighbour, most advancing neighbour, and the first future contact) rather than just one criterion (Probability of delivery success) in the case of PROPHET, the successful node selection in ORION prevents packets from being lost; i.e., sent to nodes that cannot forward them. This allows ORION to successfully deliver more packets than PROPHET as shown in Figure 50. From this figure, we can also notice that the impact of nodes' speed is more important in ORION than in PROPHET. With a high speed, the accuracy of the ARMA predictions is affected since the contacts' durations will be at the same scale as prediction error margin. Thus, packets loss will be more frequent. However, the packet delivery ratio is still higher than Prophet's.

4.4.2.3 First Packet Arrival (FPA) and End-to-End Transmission Delay (EED):

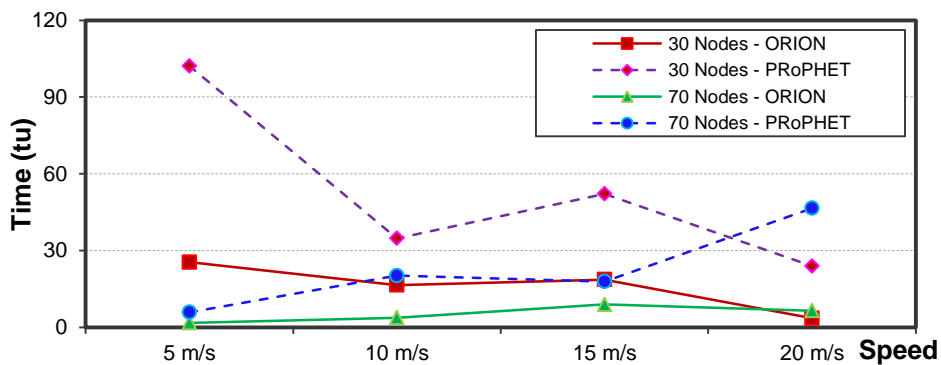


Figure 51: First Packet Arrival in 30 and 70 nodes topologies with variant speed.

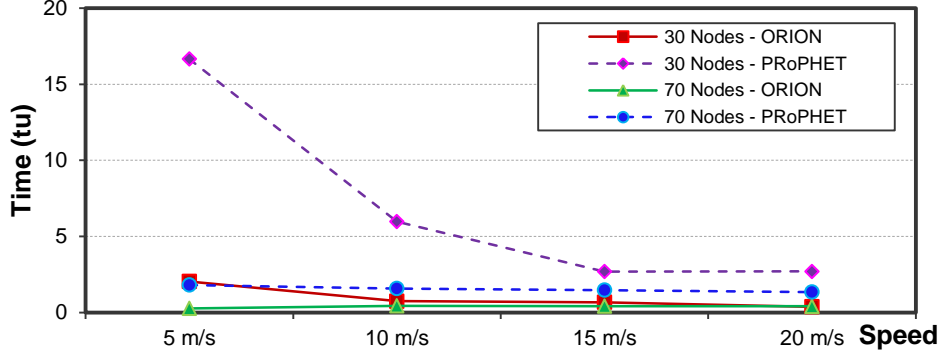


Figure 52: Average E2E Delay in 30 and 70 nodes topologies with variant speed.

Because of the greedy nature of ORION, packets will always choose either the shortest or the "earliest" next hop making packets arrive more quickly at the destination node (Figure 51) and experiencing shorter end-to-end delay (Figure 52) compared to PRoPHET where the next hop is chosen based on only its success delivery probability.

4.4.2.4 Bundle Queue Occupancy:

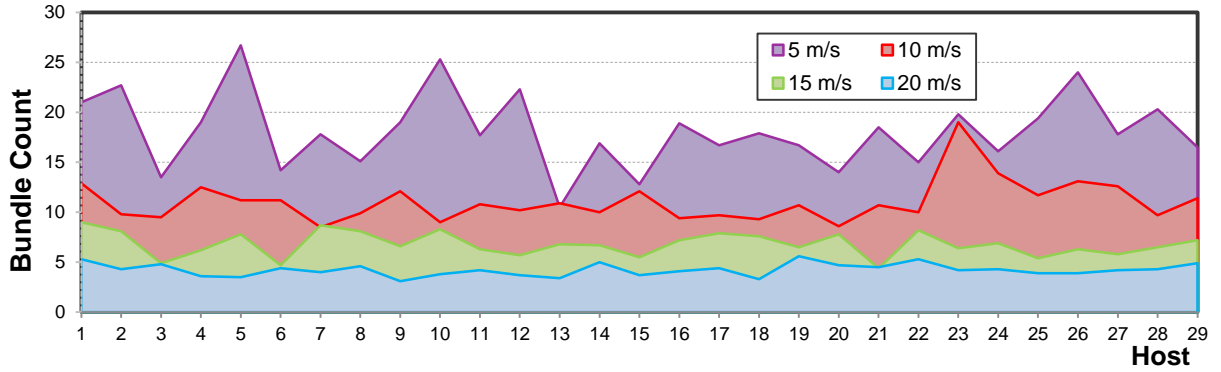


Figure 53: Maximum message queue occupancy in 30 nodes topologies with variant speed.

From Figure 53 we can clearly see that ORION routing protocol does not require excessive memory space for message queue in order to achieve store-and-forward routing. In our simulations, and in sparse network topology (30 nodes), the maximum message queue occupancy is high (~ 26 messages in case of 5 m/s node mobility speed) when the node mobility speed is slow. Due to the rarity of the contacts, nodes are obliged to keep messages for a long period of time. However, with higher node mobility speeds, the maximum queue occupancy decreases accordingly (maximum of ~ 5 messages in the case of 20 m/s node mobility speed). Furthermore, in dense network topology (70 nodes), the maximum message queue size is bound to ~ 2 messages which it is more than acceptable.

4.5 Conclusion

In this chapter, we have described a new routing protocol, dubbed as ORION, which is suitable for mobile delay tolerant networks. Since the network dynamics are often not so random such as in city-wide inter-hotspot network interconnected through taxis, buses and vehicles, the contacts between two communicating nodes can be analysed and, moreover, predicted. ORION routing protocol is based on greedy geographic forwarding and contacts predictions, switching between store-and-forward and store-carry-and-forward strategies in such a way, that packet forwarding is always optimal. ORION uses ARMA model online parameter estimation to predict future contacts due to its outstanding fit to this kind of network dynamics. Simulation results show that ORION routing protocol outperforms PRoPHET in terms of different metrics such as first packet arrival delay, end-to-end transmission delay, hop count, and Packet Delivery Ratio. Moreover, ORION routing protocol does not require excessive memory space to achieve efficient delay-tolerant routing.

Chapter 5

5 Stochastic Topology Control in Wireless Sensor Networks

5.1 Introduction

The success of some applications of wireless sensor networks depends greatly on the aimed network topology, since it will impact the main tasks such as the routing protocol and the data collection scheme, but also the energy consumed for radio communications.

Considering various applications of WSN (for example, battlefield surveillance), sensor nodes can rarely be deployed in a deterministic way. Thus, random node deployment is often the only solution. However, such deployment has some disadvantages. First, if dropped, sensor nodes are not guaranteed to be still functional once on the ground. Moreover, some embedded hardware like those for localization (Positioning systems, Angle measurement, etc.) or even the hardware for communication (i.e. the radio antenna) can be damaged or will not function properly. Second, the network topology is unpredictable and this will impact heavily all the networking tasks such as node organisation, data gathering, packet forwarding, etc. Consequently, and in order to ensure the desired application, nodes may consume more energy in various tasks:

- (1) Nodes may have to transmit the data packets over long distances and thus consume more energy in communications, as shown in Figure 54.
- (2) A node may become a cluster-head in a hierarchical organization, with less capability, less residual energy, etc.
- (3) A node may become a hot spot in order to keep the global connected topology from being partitioned, as shown in Figure 55.

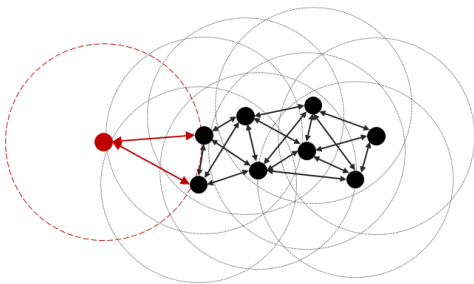


Figure 54: Transmission over Long Distances

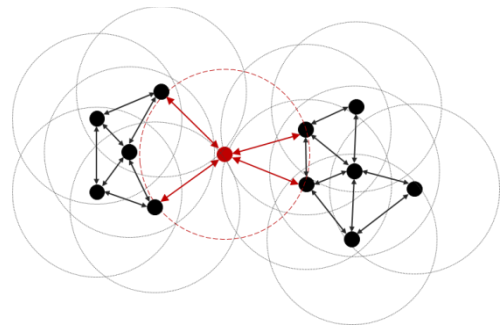


Figure 55: Hot Spot Node

These network topology issues have received a lot of attention in the literature. On the one hand, a lot of research works have been carried out in order to optimize the WSN applications by making them aware of the underlying network topology. Thus, a lot of routing protocols have taken advantage of geographic information (coordinates, angle, distances, etc.) in order to make packet forwarding decisions. These geographic routing protocols rely on greedy forwarding to route the data packets from the source to the final destination [49][121] with high efficiency and low energy consumption. A lot of these protocols addressed the problem of topology holes that may be formed due to various reasons (nodes' deployment, nodes' mobility, nodes' failure, etc.). Techniques such as face routing in planar graphs [53] or step-back-and-mark [151] have been used. On the other hand, the trend is for approaches that optimize the WSN using topology control. These approaches act on the topology. Towards this objective, we can find techniques where nodes adjust their transmission range in order to adjust the one-hop neighbourhood size [44][152][153][154][155]. In some other techniques, node may act on their wake/sleep scheduling [50][54][156][157] to achieve an optimized network topology where lesser nodes are active, and thus maximizing the global network lifetime. These topology adjustment approaches can be divided into two main categories: (a) sensing coverage topology control, and (b) connectivity topology control. The first category aims to optimize the surface area being covered by the node's sensing hardware (for example, the angle of view of a camera). The optimization concerns the maximization of the surface being sensed, but also the minimization of the number of sensor being involved [158][159][160][161][162][163][164]. While, the second category aims to optimize the communication infrastructure by maintaining the nodes connected and keeping the whole network from being partitioned into disconnected clusters [44][50][54][152][153][154][155][156][157][165].

5.2 Related Work

Topology issues have been widely studied in the literature, a coherent taxonomy is given in [166]. Topologies control problems are divided into two main categories: (1) Sensor coverage topology, and (2) Sensor connectivity topology. The first one is concerned about maximizing the sensing area while consuming less energy, whereas, the second one is concerned about network connectivity.

5.2.1 Sensor Coverage Topology

Sensor coverage can be studied in static, mobile and hybrid networks.

- *Static Networks*: all the nodes are static and their location is a direct result of the node deployment. Many approaches have been proposed targeting different levels of sensing coverage: (1) partial sensing coverage [164][167], (2) single sensing coverage

[168], and (3) multiple sensing coverage [160][162][163]. In partial coverage, only partial area is sensed within a certain period of time. In single coverage, nodes try to sense non overlapping areas in order to cover the entire sensing field. Finally, in multiple coverage, an area is covered redundantly by more than one node.

- *Mobile Networks*: nodes are mobiles and move to their best location in order to optimize the sensing coverage. Works in [158][159][161] studied the best relocation schemes in order to achieve efficient sensing coverage.
- *Hybrid Networks*: only some nodes are capable of moving. They can help the achievement of a desired coverage by moving to their best computed locations. Authors in [168] proposed a combined solution for the exploration and the coverage of a given area. Authors in [170] considered single sensing coverage problem by relocating mobile nodes to overcome topology holes.

5.2.2 Sensor Connectivity Topology

In this context, energy can be reduced according to two main schemes. The first one concerns the adjustment of the transmit power, resulting in adjusted transmission range. The second scheme concerns the decision making about which nodes should be turned on/off, when, and for how long.

- *Power Control Mechanisms*: the goal is to dynamically change the transmitting range in order to maintain some property of the communication graph, while minimizing the node's energy consumption. Works in [44][152][153][154][155][165][171] fall into this category.
- *Power Management Mechanisms*: the goal is to decide which of the nodes should be turned on/off and when in order to build an energy saving topology and thus to maximize the network lifetime. Works in [50][54][156][157] fall into this category.

5.2.3 Discussion

Wireless sensor networks are a very promising technology. Indeed, the philosophy behind this technology is that with lower costs, WSN-based applications can perform as well as applications that rely on solid in

A lot of WSN applications do not require the use of mobile sensor nodes although it may enhance greatly the considered application. Making the sensor nodes mobile capable require the embedding of a whole different hardware (wheels, engines, etc.) and require more energy (mobility hardware is much energy consuming than any of the classic nodes' functions). Moreover, such

sensor nodes will cost much more than static sensor nodes which will be against the WSN philosophy. However, some applications (critical, harsh environments, etc.) cannot do without it.

Sensing range is often distinct from the radio communications range. Thus building a network topology for optimizing the coverage differs depending on the coverage type to maximize (sensing or communication). Regarding the targeted application, certain coverage can be more important than the other. For applications where nodes do transmit data very often, it is required to optimize the packet forwarding infrastructure, since radio communication is the most energy consuming task in wireless sensor networks.

In some WSN-based applications, sensor nodes are randomly and densely deployed which may be very inefficient in terms of data gathering, network lifetime, etc. Indeed, dense deployment present some issues such as radio jamming that may make the nodes retransmit their data packets very often if the MAC layer handles retransmissions, else communications will suffer from severe packet loss. Another issue concerns the network lifetime, if no energy management mechanism is implemented, nodes will be always on a wake state. This lead to the fact that a large number of nodes will be involved for a packet forwarding that may concern just few nodes, since all the neighbouring nodes are hearing the radio transmissions. Moreover, such deployment will increase the delays due to the scheduling effort required for the transmissions' synchronization in a dense deployment.

Wireless sensor networks are often densely deployed, and an efficient packet forwarding infrastructure is thus required in order to maximize the network lifetime by making the nodes live longer. Since the radio communication task is the most energy consuming, such infrastructure can be achieved through an efficient on/off schedule of the radio hardware at each node. The challenge is then to design a distributed nodes' activity schedule that tries to put a large number of nodes in an off state while ensuring that every data packet can still be successfully forwarded to its destination, i.e. the obtained topology still offers a path from the source to the final destination of the packet.

5.3 System Model

In order to design an energy-efficient activity schedule, we need to address the following points:

- (1) What is the algorithm to run at each sensor node in order to decide whether to put the radio hardware in off state (entering the sleep mode)?
- (2) How long should a sensor node remain in the sleep mode?

5.3.1 Node Deployment

In the following, we consider a predetermined sensing field (we consider rectangular sensing field for simplification, having a length of L and a width of W). N nodes are deployed randomly across this sensing area. All sensor nodes are homogeneous in terms of sensing hardware, communication range and initial energy provision. The radio transmission range of each node is equal to R . Radio transmission range is uniformly a disk with a radius equal to R . Thus, the generated communication graph is a unit disc graph.

We call "*neighbour*" of node i , every node j such as the distance between i and j is lower than R . the number of one node's neighbours depends on the initial node deployment mode and the sensing field's surface.

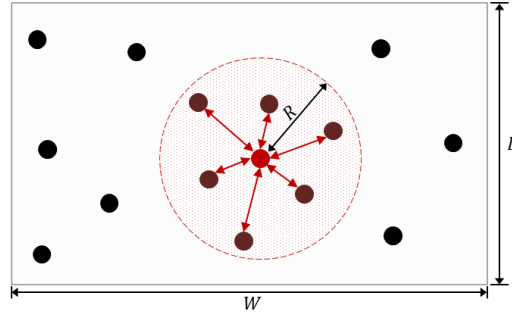


Figure 56: Neighbouring Probability in Uniform Deployment

For *uniform deployment*, the average number of neighbours can be computed as follows:

The probability for a node j to be a neighbour to node i can be expressed as the probability of the node j being deployed inside the transmission range of node i , i.e. the coordinates of node j (x_j, y_j) fall within the disc having as centre the node i coordinates (x_i, y_i) and R as its radius (see Figure 56). Thus, this probability can be:

$$P(\text{Neighborhood}) = \frac{\text{Disc_Surface}}{\text{Field_Surface}} \quad (5.1)$$

$$P(\text{Neighborhood}) = \frac{\pi R^2}{LW} \quad (5.2)$$

Thus, the average number of neighbours, \bar{M} , is equal to:

$$\bar{M} = (N - 1) \frac{\pi R^2}{LW} \quad (5.3)$$

However, experimental data shows results that differ from theoretical results due to the border effects [172]. Indeed, nodes that are located at the border of the rectangular sensing field have fewer neighbours than nodes that are fully located within the sensing field. The average neighbours count has been investigated in [173] through simulations. Authors conclude that, if border effect is negligible, a binomial approximation is enough accurate to estimate the neighbourhood size. Works in [172][174] show that the average neighbours count can be approximated by the following formula:

$$\bar{M} = \frac{(N-1)}{L^2W^2} \left(\frac{1}{2}R^4 - \frac{4}{3}LR^3 - \frac{4}{3}WR^3 + \pi LWR^2 \right) \quad (5.4)$$

5.3.2 Wakeup/Sleep Schedule

For random node deployment, the average number of neighbours is considered uniform and it equals \bar{M} . In order to decide the duration of each state: sleep and awake, a node can simply choose durations according to two any statistical distribution such as *Poisson*, *Pareto*, *Log-Normal*, etc. the benefit from such duration selection method is that each node can choose its values without any additional knowledge about its neighbourhood. In the following, we analyse the consequences of such schedule in terms of neighbourhood size.

We consider a WSN where all nodes are deployed uniformly across the sensing field. Every node is choosing its wake-up duration according to a Poisson distribution with parameter λ , followed by a sleep period of a duration that follows a Poisson distribution with parameter μ . Figure 57 represent the number active neighbours in this context.

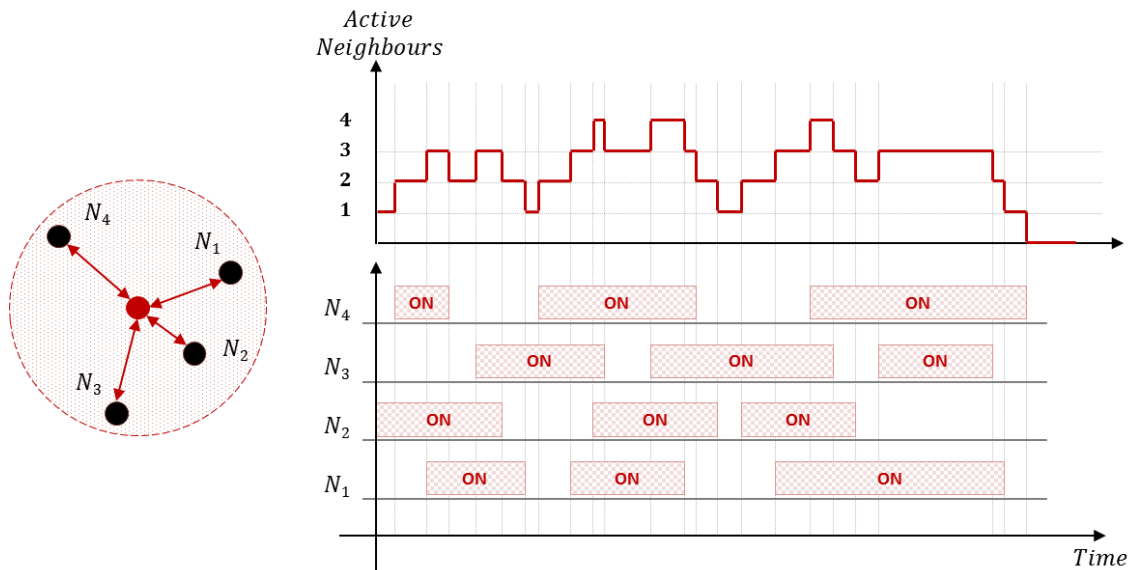


Figure 57: Number of Active Neighbours

The wakeup/sleep process is an On/Off Markov Process $\{X_t; t \in \mathcal{R}_+\}$, having the following transitions probabilities: $Q(ON, OFF) = Q(OFF, ON) = 1$, and $Q(ON, ON) = Q(OFF, OFF) = 0$ (a wakeup state is automatically followed by a sleep state and vice versa). The average wakeup state duration is $q(ON) = \lambda$, and $q(OFF) = \mu$. This leads to the following infinitesimal generator:

$$A = \begin{pmatrix} -\mu & \mu \\ \lambda & -\lambda \end{pmatrix} \quad (5.5)$$

Solving the equation $\pi A = 0$ let us find the stationary probability that a node is on a sleep state or a wakeup state:

$$\pi_{ON} = \frac{\lambda}{\lambda + \mu} \text{ and } \pi_{OFF} = \frac{\mu}{\lambda + \mu} \quad (5.6)$$

If we consider the superposition of M homogenous and independent On/Off Markov processes $\{X_{i,t}; t \in \mathcal{R}_+, i = 1, \dots, M\}$, we will have the aggregated process $Y_t = \sum_{i=1}^M X_{i,t}$ taking its states in $\{0, 1, \dots, M\}$. State 0 is when all the processes are on OFF state and M when all the processes are on ON state.

- If the process is in the state $Y_t = 0$, the only possible transition is $0 \rightarrow 1$ corresponding to the end of one of the OFF periods, so the average duration in this state is $q(0) = M\mu$.
- Respectively, if the process is in the state $Y_t = M$, the only possible transition is $M \rightarrow M - 1$ corresponding to the end of one of the ON periods. So the average duration in this state is $q(M) = M\lambda$.
- In the state $Y_t = i, 0 < i < M$, the next possible transitions are:
 - $i \rightarrow i + 1$, if there is an OFF period ending among the $M - i$ OFF periods at this instant.
 - $i \rightarrow i - 1$, if there is an ON period ending among the i ON periods at this instant.

Thus, the duration of the state $Y_t = i$ is the minimum of two variables A and B , the first one of parameter $(M - i)\mu$ that corresponds to the transition towards $i + 1$ and the second one of parameter $i\lambda$ that corresponds to the transition towards $i - 1$. Thus, $q(i) = (M - i)\mu + i\lambda$.

Then, we have the following transitions probabilities:

- $Q(0, 1) = 1$
- $Q(M, M - 1) = 1$
- For $0 < i < M$:
 - $Q(i, i + 1) = P(A < B | Y_t = i) = \frac{(M - i)\mu}{(M - i)\mu + i\lambda}$

$$\blacksquare \quad Q(i, i-1) = P(B < A | Y_t = i) = \frac{i\lambda}{(M-i)\mu + i\lambda}$$

Leading to the following infinitesimal generator:

$$A = \begin{pmatrix} -M\mu & M\mu & 0 & 0 & 0 & 0 & \cdots \\ \lambda & -((M-1)\mu + \lambda) & (M-1)\mu & 0 & 0 & 0 & \cdots \\ 0 & 2\lambda & -((M-2)(\mu + 2\lambda)) & (M-2)\mu & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ 0 & 0 & 0 & 0 & 0 & M\lambda & -M\lambda \end{pmatrix} \quad (5.7)$$

To get the stationary probability distribution π , we solve the equation $\pi A = 0$. Putting $\rho = \frac{\mu}{\lambda}$, we get:

$$\pi_0 = \frac{1}{(1 + \rho)^M} \quad (5.8)$$

$$\pi_i = C_M^i \frac{\rho^i}{(1 + \rho)^M} \quad (5.9)$$

5.3.3 Target Wakeup/Sleep Schedule

Thus, the probability to have an average number of k active neighbours among an average of M neighbours can be computed following (5.4). In a densely deployed network, it would be profitable if the maximum number of nodes can be put in a sleep state without disconnecting the nodes. Towards, this objective, reducing the size of active neighbourhood seems promising. Indeed, to forward data packets, a node need only one neighbour. However, since every neighbour is not always located in the best direction towards any destination node, reducing the active neighbourhood to a smaller set is more appropriate.

The question that arises after we have computed the probability to have i active neighbours among a total of M neighbours, is how to maximize this probability. This probability function is represented in Figure 58.

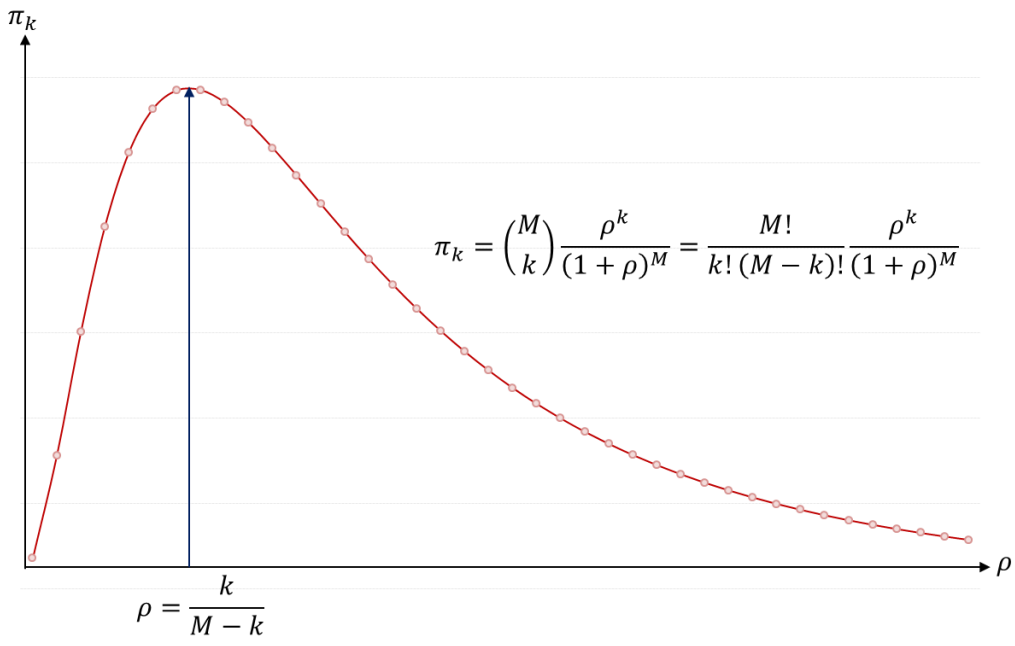


Figure 58: Probability to have K neighbours

The probability function $\pi_k(\rho)_{k,M}$ exhibits a maximum at the point:

$$\rho^* = \frac{k}{M - k} \quad (5.10)$$

Thus, the best wakeup/sleep ratio (ρ) in order to maximize the probability to have an average of k active neighbours among an average of M neighbours is the value ρ^* .

In order to optimise the active neighbourhood size, a general approach is to tune the wakeup/sleep schedule in such a way to maximize the probability to have the active neighbourhood size contained in a certain interval $[u, v]$, with $u > 0$ (in order to not disconnect the node from the network) and $v < M$ (in order to use less neighbours than the actual neighbours count). This probability, $P_{[u,v]}$, can be expressed as the following:

$$P_{[u,v]} = P(u \leq N(t) \leq v) = \sum_{k=u}^{k=v} \pi_k \quad (5.11)$$

$$P_{[u,v]} = \pi_{[u,v]} = \sum_{k=u}^{k=v} C_M^k \frac{\rho^k}{(1 + \rho)^M} \quad (5.12)$$

$$P_{[u,v]} = \pi_{[u,v]} = \frac{1}{(1 + \rho)^M} \sum_{k=u}^{k=v} C_M^k \rho^k \quad (5.13)$$

The probability function $\pi_{[u,v]}(\rho)_{u,v,M}$ is shown in Figure 59. This function exhibits a maximum for the value $\widehat{\rho_{[u,v]}^*}$. We can see that this function includes a partial sum of the binomial formula $(1 + \rho)^M$. It is worth to notice that no closed form exists for such sum.

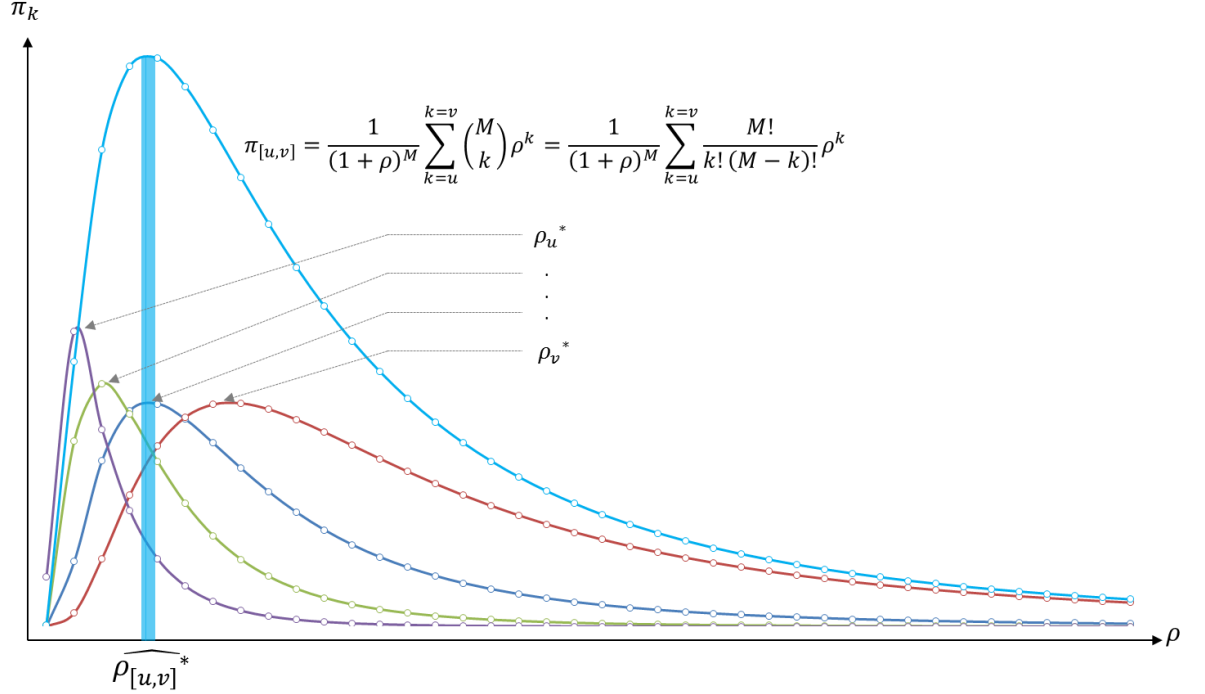


Figure 59: Probability to Have [u,v] Active Neighbours

Finding $\widehat{\rho_{[u,v]}^*}$ requires solving for ρ the equation:

$$\pi'_{[u,v]}(\rho)_{u,v,M} = 0 \quad (5.14)$$

$$\frac{1}{(1 + \rho)^{M+1}} \sum_{k=u}^{k=v} C_M^k \rho^{k-1} (k - \rho(M - k)) = 0 \quad (5.15)$$

$$\sum_{k=u}^{k=v} C_M^k \rho^{k-1} (k - \rho(M - k)) = 0 \quad (5.16)$$

Solving this equation is equivalent to find the root of a $(v - u + 1)$ -degree polynomial. This equation may be complex to solve when the degree of the polynomial increases. Thus, approximation techniques can be. By using the Newton's method, the solution to this equation can be found very quickly.

Given the function g and its derivative g' :

$$g(\rho) = \sum_{k=u}^{k=v} C_M^k \rho^{k-1} (k - \rho(M - k)) = 0 \quad (5.17)$$

$$g'(\rho) = \sum_{k=u}^{k=v} k C_M^k \rho^{k-2} (k - 1 - \rho(M - k)) = 0 \quad (5.18)$$

Then, an efficient process for calculating a good approximation of the value $\widehat{\rho_{[u,v]}^*}$, is:

$$\rho_{n+1} = \rho_n - \frac{g(\rho_n)}{g'(\rho_n)} \quad (5.19)$$

5.3.4 Local Topology Awareness and Path Construction

We consider WSN-application where nodes are organized into a flat topology. Every node implements a heart-bit application designed to advertise its distance towards the sink node in terms of number of wireless hops.

Every node keeps in its local memory information about how to reach the sink node. This information include its distance towards the sink node in terms of hop count (*HopsToSink*) and the neighbour (*NextHop*) through which to send all data packets addressed to the sink node (packets generated locally or packets to be relayed).

$$BeaconPacket = \{SenderID, HopsToSink\}$$

At the start-up of the application, the sink node broadcast a beacon packet containing a field "*HopsToSink*" equal to 0. At the reception of this packet, every node will update its information on how to reach the sink node if a best forwarder node is found. If not, the node's local information are not updated. The node will then broadcast its beacon packet with the up-to-date information. Figure 60 represents this process.

Upon_Receiving_a_Beaon(pk)

Parameters:

HopsToSink: a variable to store the distance to the sink node in terms of hops (initially set to $-\infty$)

NextHop: the forwarder neighbour through which to reach the sink node (initially set to \emptyset).

not have a forwarder now, so their local information (HopsToSink, NextHop) will be set to their initial values $(-\infty, \emptyset)$. The beaconing process is activated progressively wider, until all nodes will have a path to reach the sink.

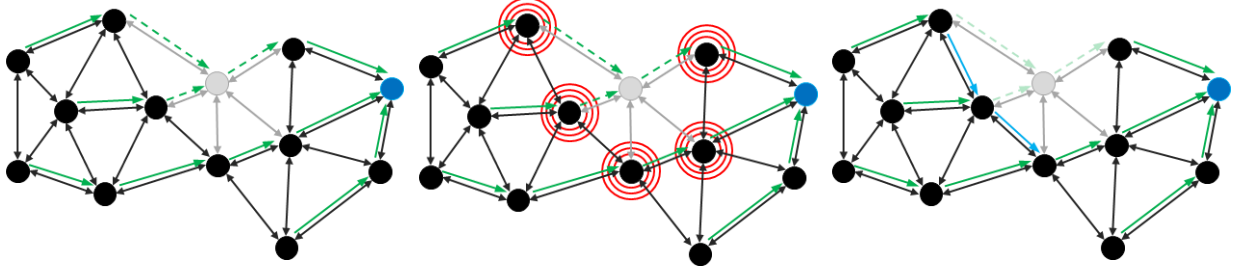


Figure 62: Example of Path Recovery

5.3.5 Data Packet Forwarding

Since paths are set up in a more static way, data packets forwarding is made simple. Indeed, every time a node receives a data packet that needs to relay, this node will forward the packet through its NextHop neighbour. Whenever, this neighbour is not available (neighbour node entering sleep state, or neighbour node failure) the data packet is then kept into a queue (PacketQueue) waiting for the path repair mechanism in order to select a new neighbour for forwarding data packets to the sink node. Figure 63 represents this forwarding algorithm.

<i>Upon_Receiving_a_DataPacket(pk)</i>	
Parameters:	
<i>HopsToSink</i> :	a variable to store the distance to the sink node in terms of hops.
<i>NextHop</i> :	the forwarder neighbour through which to reach the sink node.
<i>PacketQueue</i> :	a queue to store all outgoing data packets, ready to be sent.
<i>ID</i> :	the identifier or the local wireless node.
<hr/>	
if (<i>pk</i> .DestinationID = <i>ID</i>) then	
ProcessPacket(<i>pk</i>); // packet reached its destination	
goto EXIT;	
if (<i>NextHop</i> ≠ ∅) then	
SendPacket(<i>pk</i> , <i>NextHop</i>); // packet forwarded	
goto EXIT;	
LATER:	PacketQueue.Push(<i>pk</i>); // sending delayed until path recovery
EXIT:	end;

Figure 63: Packet Forwarding Algorithm

5.4 Performances Evaluation

5.4.1 Simulation Environment

In order to prove the performance of our stochastic wakeup/sleep scheduling, we have considered a homogenous MWN, in which, nodes are randomly deployed through the sensing field. The sensing field is a rectangular area of 1000m x 500m. The sink node is situated at a fixed point in the righter edge of the sensing field at coordinates (980, 250). We have considered this network for a monitoring application with an event-driven data gathering scheme. In response to an event, the involved node will send a data packet to inform the sink node about the occurred event.

To demonstrate and evaluate the performance of our proposed mechanism, we used OMNeT++ 4 which is a discrete event network simulator [131]. Table 2 summarizes the simulation environment.

Parameter	Value
Sensing field	1000m x 500m
Transmission Range	$R = 120\text{m}$
Number of sink nodes	1
Number of nodes	$N = \{100, 150, 200, 250\}$
Wakeup/Sleep ratio (ρ):	$\rho = \{\rho_2, \rho_3, \rho_4, \rho_{20\%}, \rho_{40\%}, \rho_{60\%}, \rho_{80\%}\}$
Wakeup Rate (λ)	$\lambda = \{\lambda_2, \lambda_3, \lambda_4, \lambda_{20\%}, \lambda_{40\%}, \lambda_{60\%}, \lambda_{80\%}\} \text{ s}^{-1}$
Sleep Rate (μ)	$\mu = 0,01 \text{ s}^{-1}$
Average Data Event frequency (δ)	$\delta = 200\text{s}$

Table 2: Simulation Parameters (Topology Control)

The following table presents the simulation parameters related to the wakeup/sleep scheduling. For each node count (N), an average neighbour count (M) is calculated according to the formula described in (5.4) due to random deployment. For each configuration (N, M), we considered different values for the ratio ρ . These values have been chosen in such a way to have 2, 3, 4 average awake neighbours and generally 20%, 40%, 60%, 80% of the total neighbours. These values are consolidated in Table 3. For example, in the defined sensing field, and using random deployment of 200 nodes, the best value for the wakeup/sleep ratio (ρ) to have the best probability to in order to have an average of 3 awake neighbours is $\rho = 0.20$, i.e., a sleep ratio that is five times greater than the wakeup ratio.

N	$\sim M_1$	$\sim M_2$	ρ_2	ρ_3	ρ_4	$\rho_{20\%}$	$\rho_{40\%}$	$\rho_{60\%}$	$\rho_{80\%}$
100	9	8	0,29	0,50	0,81	$\rho_2=0,21$	$\rho_3=0,52$	$\rho_5=1,05$	$\rho_6=2,14$
150	13	11	0,17	0,29	0,42	$\rho_2=0,21$	$\rho_5=0,52$	$\rho_7=1,05$	$\rho_9=2,14$
200	18	15	0,12	0,20	0,29	$\rho_3=0,21$	$\rho_6=0,52$	$\rho_9=1,05$	$\rho_{12}=2,14$
250	23	19	0,10	0,15	0,22	$\rho_4=0,21$	$\rho_8=0,52$	$\rho_{12}=1,05$	$\rho_{15}=2,14$

Table 3: Simulated Values for Wakeup/Sleep Ratio

For each such defined experiment we have measured various metrics:

- *Average Awake Neighbours*: this metric represents the average awake neighbours when the node is in aware of its local neighbourhood, i.e., when the local node is awake. This average is weighted by the duration of each *AwakeNeighbourCount* value.
- *Scheduled States Distribution*: this metric represents the amount of time spent in both states: wakeup and sleep.
- *End-to-End transmission Delay*: this metric to show the distribution of the necessary timespan between the instant when a data packet has been originated at its source, and the instant when it has been safely received by the sink node. This delay includes all the hops' transmission duration, but also the time spent in queues across the intermediate nodes waiting for a path to be set up/repared.
- *Packets Queue Occupancy*: this metric represents the distribution of the size of the buffer queues used to store messages waiting to be sent.

5.4.2 Simulation Results

- *Average Awake Neighbours*: from figures Figure 64-Figure 65-Figure 66-Figure 67, we can clearly see that the estimated average awake neighbours computed theatrically thanks to formulas in (5.10) and (5.19) are confirmed through simulation results.

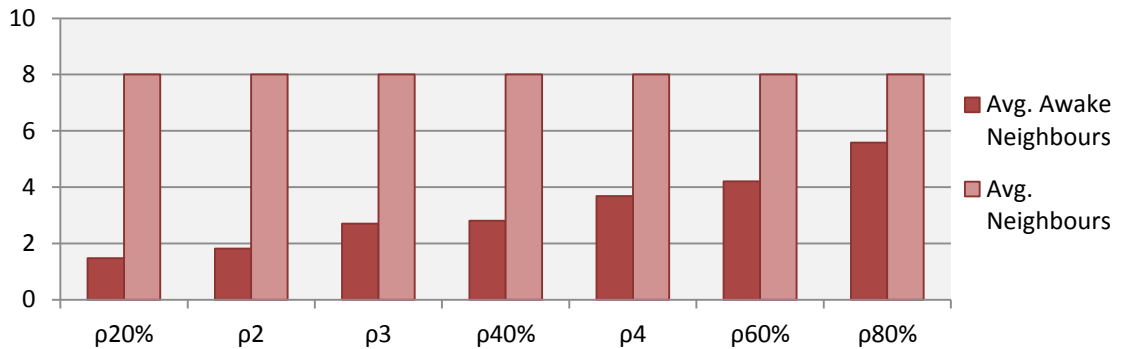


Figure 64: Average Awake Neighbours in 100 Nodes Network

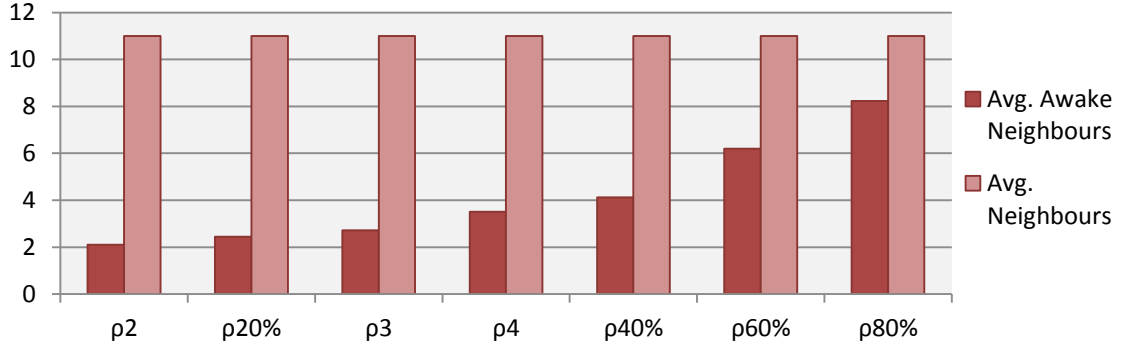


Figure 65: Average Awake Neighbours in 150 Nodes Network

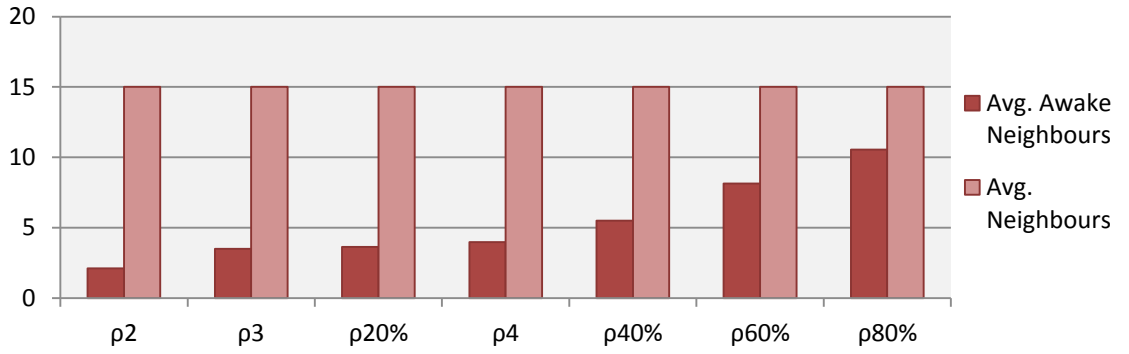


Figure 66: Average Awake Neighbours in 200 Nodes Network

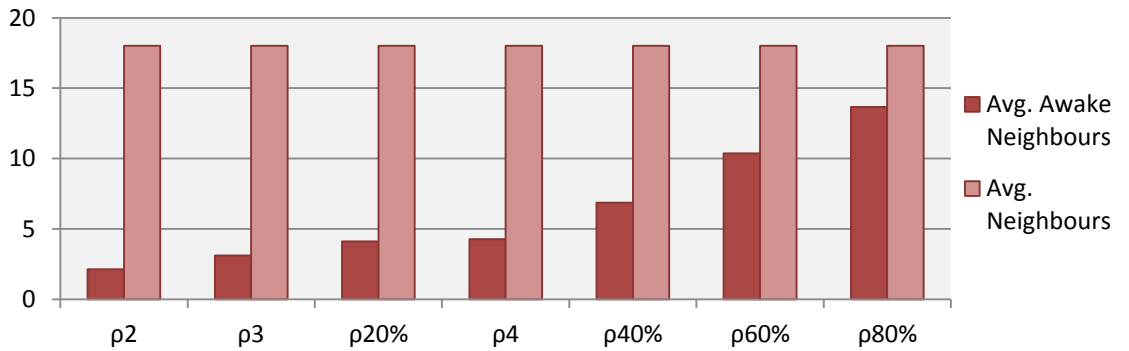


Figure 67: Average Awake Neighbours in 250 Nodes Network

Thus, the formulas in (5.10) and (5.19) are good means in order to compute the target wakeup/sleep ratio (ρ) in order to have a desired number of the average number of neighbours. In event-driven applications which use dense network deployment, candidates for packet forwarding can be numerous. Ideally, 4 neighbours at the four directions can be used in order to forward packets towards any destination node in the network. This number can be either reduced to 3 or increased to 4 or other lower/higher values depending on the distribution of the different potential destination nodes. However, in monitoring applications, where all communications occur for any node towards the sink node, it is more important to keep the topology connected by maintaining at least 1 or 2 neighbours

than to allow an easy data packet forwarding in all directions by maintaining a larger number of neighbours.

- *Scheduled States Distribution*: Figure 68 shows the distribution of the average sleep duration according to the different wakeup/sleep ratios and through different topologies (100, 150, 200 and 250 nodes). In this figure, we can see the chosen ratios (?) result in different sleep durations. Intuitively, the lower the targeted neighbourhood size, a large number of nodes switch more frequently and for long periods to the sleep state. Thus, the overall average sleep duration is higher (ρ_2 , ρ_3 , ρ_4). Moreover, we can see a correlation between the percentage of awake neighbours among the total neighbours and the percentage of the sleep duration among the node lifetime ($\rho_{20\%}$, $\rho_{40\%}$, $\rho_{60\%}$, $\rho_{80\%}$).

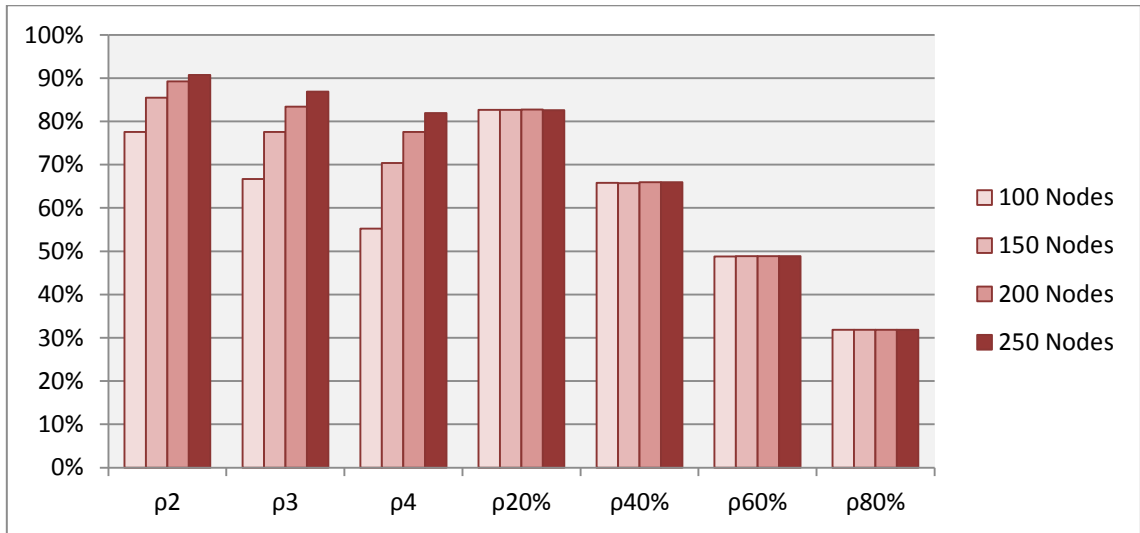


Figure 68: Average Sleep Duration (%) of the Network

- *End-to-End Delay*: Figures Figure 69-Figure 70-Figure 71 represent the average end-to-end delay for different event-generation average intervals. For this metric, every sensor node captures data events and reports them to the sink node. Interval between two captured data event is uniformly distributed with an average of 100s, 150s, and 200s. We can see that when the average awake neighbourhood size is small (2 awake neighbours), the end-to-end delay may be higher (~ 180 s). This delay decreases as the awake neighbourhood becomes more important (less than 50s for neighbourhoods where 80% of the total neighbours are awake). This increased delay is mainly explained by two factors: (1) long paths, and (2) queuing delay. Indeed, in topologies where the number of awake neighbours surrounding a node is smaller, end-to-end path may be rare, and data packets may traverse additional hops in order to reach the destination node. Moreover, data packets may arrive to an

intermediate node with no candidate forwarder. Thus, the packet is stored waiting for a forwarder to wake up or another route is found.

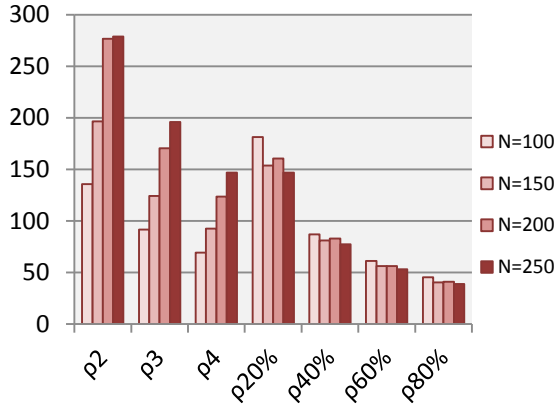


Figure 69: Average End-to-End Delay (sec) with 100s Average Event Generation Interval

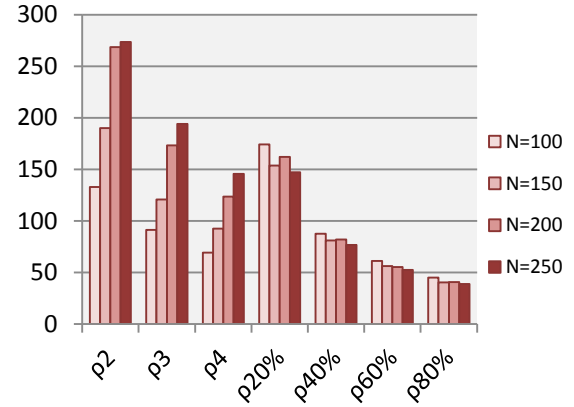


Figure 70: Average End-to-End Delay (sec) with 150s Average Event Generation Interval

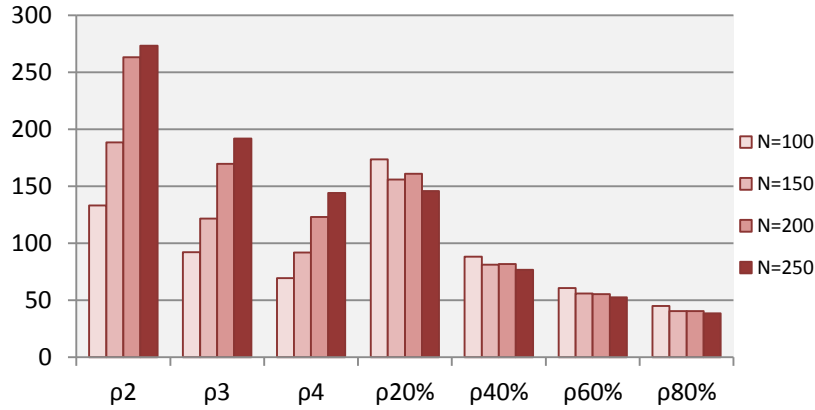


Figure 71: Average End-to-End Delay (sec) with 200s Average Event Generation Interval

End-to-end delay must be carefully taken into account. Indeed, depending on the end application, a data event can be very urgent to capture and should be rapidly reported. This can be the case in surveillance applications (battlefield, intrusion-detection, etc.). Other applications such as natural environment monitoring can tolerate important end-to-end delays.

- **Wait-to-Send Delay:** In order to look deep in the end-to-end delay, we have also measured the wait-to-send delay. This delay represents the amount of time a data packet is kept in the queue after being received or originated, waiting to be transmitted. The average wait-to-send delay for different event-generation average intervals is represented in figures Figure 72-Figure 73-Figure 74. We can see that this delay is relatively high, compared to the overall end-to-end delay. We can also notice that half the end-to-end delay is due is due to time spent on queues (i.e. wait-to-send delay).

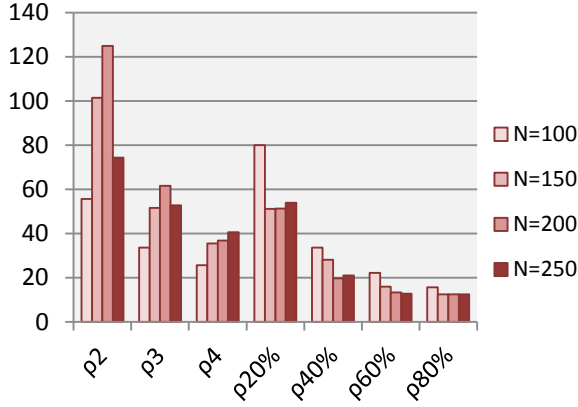


Figure 72: Average Wait-to-Send Delay (sec) with 100s Average Event Generation Interval

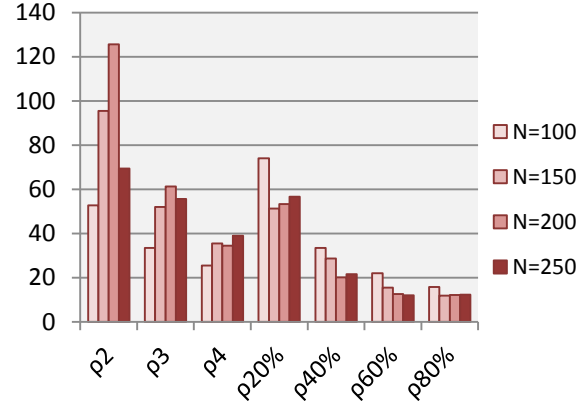


Figure 73: Average Wait-to-Send Delay (sec) with 150s Average Event Generation Interval

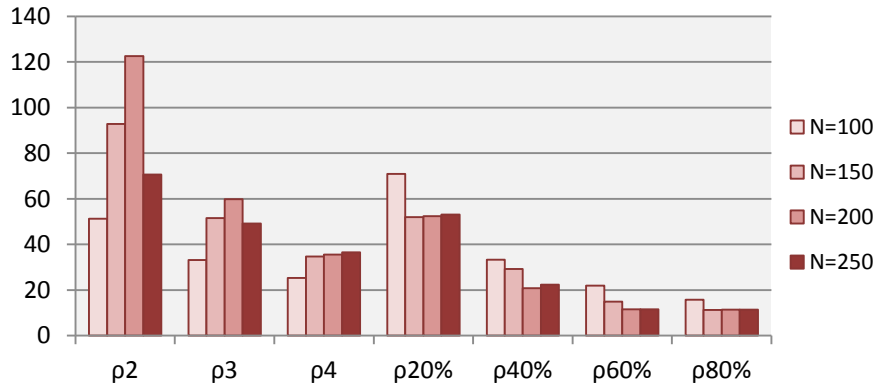


Figure 74: Average Wait-to-Send Delay (sec) with 200s Average Event Generation Interval

From the computed delays (end-to-end and wait-to-send), we can see that the larger awake neighbourhood size, the lower is the end-to-end delay.

- *Queue Occupancy*: Figures Figure 75-Figure 76-Figure 77 show the average queue occupancy in different topologies under different data event generations rates. From these figures, we can estimate the cost of the store-and-forward scheme in terms of memory space. We can notice that our proposed scheduling and packet forwarding algorithms achieves resource efficiency since the average number of packets buffered in queues waiting to be sent do not exceed the value 6 in the highest data rate (i.e. average event interval is 100s). Intuitively, these memory requirements are very low when nodes have more awake neighbours, and also when the data event rate is lower.

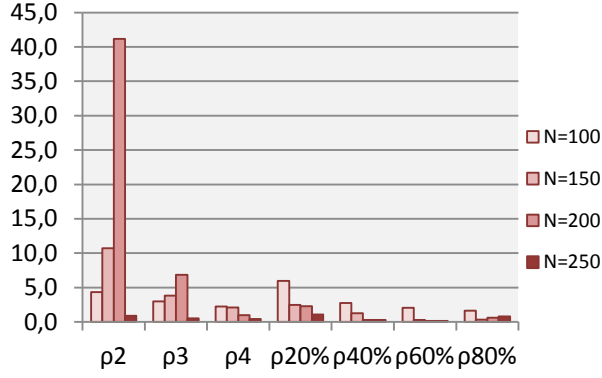


Figure 75: Average Queue Occupancy (unit) with 100s Average Event Generation Interval

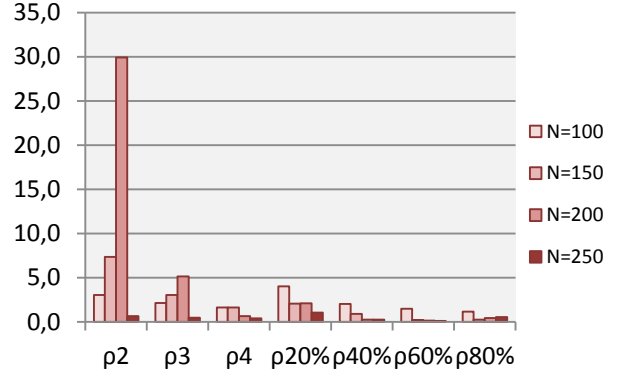


Figure 76: Average Queue Occupancy (unit) with 150s Average Event Generation Interval

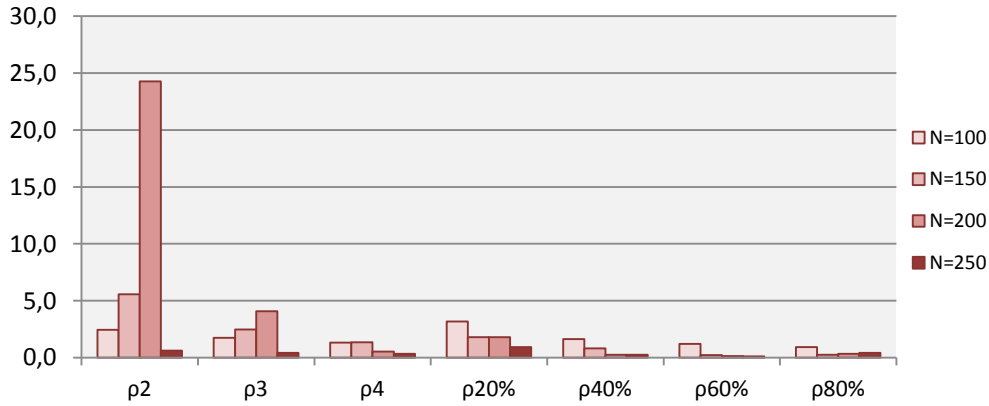


Figure 77: Average Queue Occupancy (unit) with 200s Average Event Generation Interval

Since energy conservation and low end-to-end delay are two conflicting objectives, applications should be carefully designed by finding the best trade-off between the required end-to-end delay by the application, and the targeted energy conservation.

5.5 Conclusion

In this chapter, we proposed a distributed wakeup/sleep scheduling along packet forwarding and topology construction/maintenance algorithms. The targeted applications scenarios are stationary and relatively densely deployed wireless sensor networks used for event-driven data collection. Such applications include environment monitoring, intrusion detection, etc.

We have considered random WSN deployment, and we have first studied the target wakeup/sleep ratio targeting a certain number of awake neighbours to be used as forwarders to relay messages from and through them. Second, we have described an algorithm for topology construction that is based on minimum hop count towards the destination node (i.e. the sink node). Finally, we have described a topology maintenance algorithm in order to cope with topology dynamics, and a data packet forwarding that relies on the store-and-forward scheme.

Simulations results confirmed the theoretical results and showed that the proposed mechanisms can aid the application design by allowing finding the best trade-off between application requirements (end-to-end delay and buffer space) and the targeted energy efficiency through the parameterization of the wakeup/sleep ratio.

Chapter 6

6 Conclusion and Perspectives

This chapter concludes the thesis and summarizes the major contributions while highlighting future research direction sand perspectives.

Challenged multihop wireless networks are often battery-powered. Thus, communications protocols must be energy efficient in order to maximize the network lifetime and so, the application lifetime. Moreover, due to low transmit power, wireless links are subject to various issues such as short range, radio interference, prone to errors and loss, etc. making the wireless links between the communicating nodes very unreliable. Furthermore, and depending on the application scenario, nodes may be mobile or subject to failure due to energy depletion, physical damage, theft, etc. resulting in a dynamic network topology. Along these stringent constraints, applications have demanding requirements such as low end-to-end delays, high throughput, high fault-tolerance, etc.

In this thesis, and considering the aforementioned issues, we have proposed efficient routing protocols for challenged multihop wireless networks satisfying different application's requirements while achieving resource efficiency. We believe that efficiency can only be achieved through fully distributed algorithms tending to zero control packets.

The summary of the thesis contributions is presented below.

6.1 Thesis Contributions

In this thesis, we started by studying the different characteristics of challenged multihop wireless networks, but also the principles and the open issues that govern the design of application using such networks.

As a first challenge, we have tackled the problem of bandwidth demanding applications that make use of wireless multimedia sensor networks (WMSNs). WMSNs are more and more used for video surveillance applications, intrusion detection, environment monitoring, etc. These applications have high requirements in terms of throughput, delay, packet loss, etc. such requirements can be bigger than nodes capabilities. Thus, distributed techniques must be employed in order to guarantee the service. For such applications, multipath routing might be appropriate since it allows parallel transmissions of data sub-streams that will be re-gathered at the destination node. However, the utilization of multiple paths may introduce extra overhead by generating

consequent control traffic in the network in order to explore, construct and maintain the multiple paths. In this context, we proposed an online multipath routing protocol (AGEM) that transmits multimedia streams through multiple paths established in an online fashion and without topology exploration. AGEM relies on greedy geographic packet forwarding. It ensures uniform energy consumption among the nodes of the network in order to maximize the network lifetime, and meets the applications requirements through low end-to-end delay, low packet loss ratio, and increased throughput as it has been proved through extensive simulations against single path and offline multipath routing protocols.

Second, we have tackled the problem of routing in delay tolerant networks (DTNs). DTNs can be very challenging since they suffer from intermittent connectivity. At any instant, a path between a source node and the destination may not necessarily exist. Nodes rely on multihop communications and use store-carry-and-forward scheme for packet forwarding. Applications developed for DTNs must tolerate higher delays, frequent disconnections, etc. but aim to communicate with bounded delays and by using efficiently the network resources. In this context, we have proposed an efficient routing protocol for city-wide data dissemination and collection, namely ORION. After studying the inter-node contact behavior in the case of a city-wide mobile network composed of different types of nodes (regular, irregular and static), we have derived an inter-node contact model. This model is at the center of ORION protocol, since it is used to forecast future contact dates and durations between the network nodes. Based on this information and other information such as geographic coordinates, trajectory assistance and greedy forwarding, ORION protocol performs its routing decisions. Through simulations, we have shown that ORION protocol outperforms existing protocols and achieves good performances in terms of packet delivery ratio, end-to-end delay, but also resources efficiency (memory space for packet queues).

Finally, we have tackled the problem of energy-efficient routing in stationary wireless sensor networks (WSNs) for event-driven applications. For such application and depending on the specified event frequency, some nodes can be put on a low energy-consuming state in order to maximize the network lifetime. In this context, we started by studying the distributed wakeup/sleep scheduling based on statistical distributions. We have shown theoretically, that the best schedule can be found in order to achieve a desired network topology property, represented by the average awake neighbors. Through path construction and maintenance and packet forwarding mechanisms, we have confirmed by extensive simulations our theoretical analysis. Simulation results have also shown good performances in terms of end-to-end delay, energy consumption and resources utilization (memory space for packet queues). Based on the obtained results, application

developer can derive the values of the different parameters in order to achieve a certain tradeoff between applications requirements and network resources constraints.

6.2 Perspectives

During the thesis, we have faced various challenges. Future research directions can be summarized as follows:

- *Localization Error-Tolerance*: a lot of routing protocols are assuming that nodes have the knowledge of their geographic location. Based on this information, geographical routing protocols, that make use of greedy packet forwarding, have been proposed. However, in practice, it is rarely possible to embed localization hardware within the wireless node module. Thus, nodes make use of distributed localization techniques in order to have an approximate location computed through various algorithms. These obtained locations are not error-free. Thus, routing decisions based on inaccurate information may be inefficient and may lead to energy depletion. A future direction to our works is to include localization-error into account in order to optimize the resources and to achieve good routing performances.
- *Contact model learning and Adaptability*: in our routing protocol for delay tolerant networks, the inter-node contact model has been learned and derived offline prior to application deployment. The contact model has been retained as it was empirically dominant. A future direction to this work is to make the nodes capable of learning the contact-model in an online fashion, but also to adapt in case where a learned contact model does not apply anymore.
- *Adaptive duty-cycle algorithm*: in our topology control, the scheduling parameters were computed offline and applied to the entire network in order to optimize the overall network performances. However, it would be more efficient if wireless nodes could adapt their wakeup/sleep schedule according to their local neighborhood in space (according to the resulting deployment) and time (according to neighbors' schedules).
- *Implementation of a proof of concept prototype*: all the proposed mechanisms in this thesis were proven and evaluated through either theoretical analysis or through extensive simulations. Although, resource utilization such as memory and processing power has been taken into account in all our contributions' design steps, these means are insufficient in order to prove the real performances. Therefore, we plan to implement the proposed protocols into real sensor nodes composed on Oracle SPOTs (java powered sensor nodes).

Publications

Journals

Samir Medjiah, Toufik Ahmed and Abolghasem (Hamid) Asgari "Streaming Multimedia over WMSNs: An Online Multipath Routing Protocol", *In InderScience International Journal on Sensor Networks (IJSNet), Special Issue on Multimedia Data Applications in Wireless Sensor Networks* (InderScience IJSNet).

International Conferences

Samir Medjiah and Toufik Ahmed, "ORION Routing Protocol for Delay Tolerant Networks", *In the 46th Annual IEEE International Conference on Communications 2011 (IEEE ICC 2011)*. June, 5th - 9th, 2011, Kyoto, Japan.

Samir Medjiah, Toufik Ahmed and Francine Krief, "AGEM: an Adaptive Greedy-compass Energy-aware Multipath Routing Protocol for WMSNs", in *The 7th Annual IEEE Consumer Communications and Networking Conference 2010 (IEEE CCNC 2010)*. January, 9th - 12th, 2010, Las Vegas, USA.

Samir Medjiah, Toufik Ahmed and Francine Krief, "GEAMS: a Greedy Energy-Aware Multipath Stream-based Routing Protocol for WMSNs", in *the 2nd IEEE Global Information Infrastructure Symposium (IEEE GIIS 2009)*, 23rd - 26th, June, 2009, Hammamet, Tunisia.

National Conferences

Samir Medjiah, Toufik Ahmed, Francine Krief et Patrick Gélard, "AGEM: un Protocole de Routage Géographique Angulaire Adaptatif", *Colloque Francophone sur l'Ingénierie des Protocoles 2009 (CFIP 2009)*. 12-15 Octobre 2009, Strasbourg, France.

Workshops

Patrick Gélard, Charles Yana, Emmanuel Dubois, *Samir Medjiah*, Toufik Ahmed and Francine Krief, "Hybridization Architecture of Satellite Networks with Wireless Sensor Networks", in *The ESA Wireless Sensor Networks for Space Applications Workshop 2009 (ESA WiSens4Space 2009)*, 1st - 2nd October, 2009, Santorini, Greece.

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