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Communication Primitives for Wireless Ad Hoc Networks

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Abstract

The relevance of wireless multi-hop *ad hoc* networks has been increasing in the past years due to the emergence of the Edge Computing paradigm. These networks consist of a set of devices that communicate directly with each other, by exchanging messages through the wireless medium, without resorting to any network infrastructure. As a result, they are suitable to be applied in situations where network infrastructure is inexistent, unavailable, or debilitated, such as areas affected by natural disasters, search and rescue missions, or environmental monitoring and other Internet of Things applications. In this context, a fundamental abstraction that is necessary to develop distributed applications and services is communication primitives, of which we focus on (application-level) broadcast and routing. Broadcast consists of disseminating a message so that it is delivered by all the devices and routing consists of forwarding a message so that it is delivered by a given destination.

The literature on broadcast and routing algorithms is quite vast, with numerous solutions proposed over the years that explore, or combine, different techniques. However, understanding how they relate among each other is very challenging, although it is essential to understand how different techniques behave in different practical settings and how they can be combined. Furthermore, most of these solutions have only been evaluated through simulations, which fail to accurately capture all the characteristics of wireless *ad hoc* networks. Therefore, in this thesis, we plan to study and propose novel adaptive algorithms for broadcast and routing in wireless *ad hoc* networks, that combine different existing mechanisms that are suitable for different scenarios. In addition, we plan to encapsulate these algorithms in the form of generic frameworks to enable the exploration, in practice, of new techniques for these domains.

Keywords: Wireless Ad Hoc Networks, Broadcast, Routing, Framework

Resumo

A relevância de redes *ad hoc* multi-salto sem fios tem vindo a aumentar nos últimos anos, devido à emergência do paradigma da Computação na Periferia. Estas redes consistem num conjunto de dispositivos que comunicam diretamente, trocando mensagens através do meio sem fios, sem recorrerem a qualquer infraestrutura de rede. Como resultado, elas são adequadas para ser aplicadas em situações onde infraestrutura de rede seja inexistente, indisponível ou debilitada, tais como áreas afetadas por catástrofes naturais, missões de busca e salvamento ou monitorização ambiental e outras aplicações da Internet das Coisas. Neste contexto, uma abstração fundamental que é necessária para desenvolver aplicações e serviços distribuídos é primitivas de comunicação, das quais nos focamos em difusão e encaminhamento. Difusão consiste em disseminar uma mensagem tal que seja entregue por todos os nós e encaminhamento consiste em encaminhar uma mensagem tal que esta seja entregue por um dado destino.

A literatura em algoritmos de difusão e de encaminhamento é bastante vasta, com inúmeras soluções tendo sido propostas ao longo dos anos que exploram, ou combinam, diferentes técnicas. No entanto, compreender como é que estas se relacionam entre si é bastante desafiante, contudo é essencial compreender como diferentes técnicas se comportam em diferentes cenários práticos e como podem ser combinadas. Para além disso, a maioria destas soluções foi apenas avaliada através de simulações, as quais são incapazes de capturar fielmente todas as características de redes *ad hoc* sem fios. Assim, neesta tese, planeamos estudar e propor novos algoritmos adaptativos para difusão e encaminhamento em redes *ad hoc* sem fio, que combinam diferentes mecanismos existentes que são adequados para diferentes cenários. Adicionalmente, planeamos encapsular estes algoritmos na forma de estruturas genéricas para possibilitar a exploração, na prática, de novas técnicas para estes domínios.

Palavras-chave: Redes Ad Hoc Sem-fios, Difusão, Encaminhamento, Estrutura

Contents

List of Figures

Chapter 1

Introduction

In recent times, the Edge Computing paradigm [87] has been increasing in relevance, as a consequence of mainly two factors: its emergence as a response to the limitations of Cloud infrastructures [19]; and the increasing interest in developing ubiquitous applications for the Internet of Things (IoT) or the Internet of Everything (IoE), which include the Smart Cities and Smart Homes domains.

Cloud Computing [22, 41] is the dominant paradigm for devising distributed applications nowadays, resorting to centralized infrastructures, called data centers, which are composed by servers that process and store application and user data, and with which clients remotely interact. Cloud Computing presents many advantages, such as: no need to over-provision due to resources' elasticity, pay-as-you-go pricing, and easily deploy global applications. These collectively turn cloud infrastructures into an appealing platform for devising novel applications. However, cloud platforms are not flawless, presenting several issues and limitations, for instance, they are unable to timely process high volumes of data of some applications [19, 45, 87] and end-users may experience high latency when communicating with servers. These limitations motivated the migration of computations, from within the cloud data centers, towards devices closer to end-users, leading to the rise of a new paradigm: Edge Computing [87]. Edge Computing, generally speaking, consists in performing computations outside cloud infrastructures, near data producers and consumers.

Since any device outside a data center is a potential edge device, Edge Computing has a very wide spectrum of materializations [5, 53, 77, 100]. As such, in this thesis, we chose to focus only on a particular scenario at the very edge: wireless *ad hoc* networks, formed by commodity devices[1] , that may present some mobility [19].

A wireless *ad hoc* network consists of a set of devices, capable of communicating

[1] A commodity device is any device that is relatively inexpensive and widely available.

directly with each other by exchanging messages through the wireless medium, without resorting to any network infrastructure, forming a self-organized and decentralized system. These networks have been gaining relevance lately [5, 19, 56, 77], due to their flexibility, being a solution to communicate in situations where network infrastructure is unavailable, debilitated, or not adequate, such as: regions affected by natural disasters; search and rescue missions; military missions; exploration of remote and hard to reach places; autonomous and smart vehicles; transportation systems; traffic management; smart cities and smart homes; health care; environment monitoring; multi-UAV[2] systems [8]; and personal Area Networks (PAN).

On wireless *ad hoc* networks, the devices, also called nodes or processes, can only communicate with other nodes that are within their transmission range, i.e., their (direct) neighbors. When all nodes are within the transmission range of all the others, only one transmission is required to reach the desired destination(s). In contrast, if the nodes are scattered through a wide area, due to the decaying of the radio signal strength, their transmissions cannot reach every node, and thus, nodes must cooperate, propagating (retransmiting) messages, so that these reach their intended destination(s). Therefore, protocols and applications designed for these networks have the responsibility of coordinating this cooperation. However, that can be a very complex task and thus, it can be advantageous to delegate these functionalities to several abstractions, leading to the necessity of communication primitives.

There are many communication primitives [19] and thus, in this thesis, we chose to focus on *Broadcast* and *Routing*. On the one hand, Broadcast consists of collaboratively disseminating a message, sent by a single process, so that it is delivered by all processes belonging to the system. On the other hand, Routing consists of collaboratively finding the best path to forward a message, sent by a single process, so that it reaches its single destination. We intend these communication primitives to operate at the application level, instead of being at the data link, network, or transport levels, to: *i*) allow each application or protocol to leverage specific tailored communication protocols for their particular needs; *ii*) avoid to modify the communication stack of the devices, which is not always possible in commodity devices; and *iii*) allow protocols to modify and/or process messages (*in-network-processing*) before their retransmission to, for instance, append additional information (*piggybacking*), filter messages or data, group or aggregate information, or to monitor the data being transmitted.

Problem Statement, Objectives and Expected Contributions

The literature on broadcast and routing algorithms is quite vast, having numerous solutions been proposed that explore or combine different mechanisms and techniques.

[2] UAV stands for Unmanned Air Vehicle, commonly known as drones

However, the vast majority of these solutions have been evaluated resorting only to simulations, since they provide an easy, cheap and controlled evaluation environment. Nonetheless, even the most detailed simulations may not capture the particular characteristics of real *ad hoc* environments, wrongly assuming movement patterns or communication patterns, and usually not considering hardware limitations of the wireless interfacesor sources of errors and interference in the wireless medium.Moreover, real testbeds that are employed to evaluate some solutions, generally have static grid topologies, with equidistant nodes and without external interference, which is highly unrealistic to occur in real *ad hoc* networks. On top of that, since *ad hoc* networks are extremely dynamic (in their topology, communication patterns, medium congestion, etc.), adaptive solutions that switch strategies and fine-tune parameters in run-time, are the most suitable for real *ad hoc* deployments. Thus, understanding how the many proposed solutions relate among each other, both in broadcast and routing, is crucial to devise better adaptive communication algorithms for these networks. However, their specification is not uniform, which difficults the ability to reason about the similarities and trade-offs that these algorithms may have.

Therefore, in this thesis we aim to develop application-level frameworks to simplify the development and implementation of practical communication algorithms, and leverage them to devise/improve adaptive solutions for real *ad hoc* networks, formed by commodity devices. The expected contributions of this thesis are:

- Provide two application level frameworks, one for specifying and implementing broadcast algorithms and the other for routing algorithms.
- Provide a set of implementations, leveraging the previous frameworks, for some of the most relevant algorithms as well as some adaptive solutions.
- An experimental comparison of the implemented algorithms on a real wireless *ad hoc* network, formed by commodity devices.

Thesis Structure

The remainder of this thesis is organized as follows:

- Chapter 2 presents the related work on wireless *ad hoc* networks, discussing various types of these networks and the challenges inherent to the wireless medium. We also study the most relevant broadcast and routing algorithms for wireless *ad hoc* networks.
- Chapter 3 presents the plan for the elaboration of this thesis.

Chapter 2

Related Work

In this thesis we address the challenge of designing practical communication primitives for real *ad hoc* networks formed by commodity devices. In this sense, we start this chapter by briefly discussing the fundamental concepts of wireless networks in general, and wireless *ad hoc* networks in particular (§2.1). Next, we delve into the characteristics and challenges of the wireless medium and how to mitigate them (§2.2). Finally, we conclude this chapter by presenting the broadcast problem and some of the most relevant solutions found on the literature (§2.3), followed by a discussion on the routing problem and the state of the art of proposed solutions (§2.4).

2.1 Wireless Networks

For a long time, wired networks were the only way to connect distributed systems. Subsequently, the evolution of wireless transmission technologies led to the emergence of wireless networks, which gave systems, and users, the ability to move while remaining connected to the network [60].

A wireless network consists of a communication abstraction formed by a set of devices, called nodes [1] , that exchange information through radio waves over the wireless medium.

The vast majority of wireless networks are centralized in nature and supported by an infrastructure, containing one or more devices which form and coordinate the access to these networks. Depending on the underling technology used to form the network, these devices have different names, however, for simplicity, we will refer to them as coordinators. Multiple coordinators can be interconnected with each other, forming a backbone for the network. However, this organization is not flexible, since it limits the mobility of nodes to only areas covered by the coordinators, nor scalable, considering that each

[1] also called processes, terminals, or hosts.

coordinator has a limited number of devices to which it can be connected simultaneously, and deploying more coordinators is not sustainable. Therefore, wireless *ad hoc* networks emerged as a solution to address these limitations.

2.1.1 Wireless Ad Hoc Networks

A wireless *ad hoc* network is a set of devices with wireless capabilities, formed spontaneously, that communicate directly with each other through the exchange of messages over the wireless medium, without leveraging some network infrastructure.

As previously mentioned, generally in these networks not all nodes are within the transmission range of all the others, and thus they must cooperate, by performing messages' retransmissions, so that messages arrive at their intended destination(s). Because of this, these networks are also usually called multi-hop wireless *ad hoc* networks.

The topology of these networks can be highly dynamic, since the networks are formed spontaneously; nodes may present mobility; nodes may join or leave the network at will at any given time; and unstable links, due to the inherent problems of wireless medium (discussed in §2.2).

2.1.1.1 Types of Wireless Ad Hoc Networks

Due to the great versatility of *ad hoc* networks, these can be applied to a multitude of scenarios. This led to the emergence of different specializations of *ad hoc* networks that, despite having common characteristics, have sufficient different particularities for specialized solutions to exist for each one of these types. Next, we present some of the most common ones.

Wireless Sensor Networks (WSNs) are *ad hoc* networks composed of several (ususally) resource-constrained devices with little mobility [3, 4, 19], that measure and collect information from the physical environment, like temperature, air quality, humidity, etc. These information is commonly transferred, or aggregated, into a single node, called the *sink node*, which is responsible to process it. As sensors tend to be resource constrained, minimizing their energy consumption, to preserve their batteries, is typically the main objective on these networks. *UnderWater Networks (UWNs)* [63] are specialized type of *WSNs*, tailored to operate underwater. Since electromagnetic waves are heavily attenuated in water, these networks often leverage acoustic waves to carry information, that unfortunately have very high propagation delays.

Wireless Mesh Networks (WMNs) [2] are usually employed to wirelessly extend existing network infrastructure. To achieve this, they are comprised by two distinct types of devices: *mesh routers* and *mesh clients*. *Mesh routers* are nodes with little to no mobility and are not usually resource constrained, forming a wireless backbone for *mesh clients*which is responsible to forward traffic to their intended destination(s). In turn, *mesh clients* are usually more mobile and more resource constrained, when compared to *mesh routers*. They can also contribute to the routing procedure of the network, yet usually rely on *mesh routers* to communicate with other devices connected on the network. *WMNs* are becoming extremely relevant, leading to the proposition of 802.11s [33], a new extension of the 802 protocol family tailored for wireless mesh networks.

Mobile Ad Hoc Network (MANET) [19, 56, 98] are *ad hoc* networks where nodes move freely, causing their topology to be extremely dynamic. Most of the time, whenever *ad hoc* networks are mentioned in the literature, it is typically referring to *MANETs*. The focus of research on *MANETs* is directed towards efficient routing and broadcast. *Vehicular Ad Hoc Network (VANET)* [47] are a particular type of *MANET* focused on inter-vehicle communications. In these, mobility is much higher than in *MANETs* and the movement patterns are different.*Flying Ad Hoc Networks (FANETs)* [8] are a particular type of *VANET* formed by Unmanned Air Vehicles (UAVs), which can fly autonomously or are remotely controlled. In *FANETs*, mobility is much higher than in *VANETs* and *MANETs*, and the node density is usually much lower.Unlike them however, in *FANETs*, since the nodes are flying, there is usually line of sight between the nodes. *Delay/Disruption Tolerant Networks (DTNs)* [12] are a type of *MANET* that experience frequent network partitions [2]. Therefore, full end-to-end routes are difficult or impossible to determine, and thus nodes have to carry messages and forward them when they encounter other nodes, which is called Store-Carry-Forward (SCF).

Cognitive Radio Ad Hoc Networks (CRAHNs) [35] are formed by nodes that possess radios capable of leveraging unoccupied licensed bands of the electromagnetic spectrum for communication, with the aim of avoiding the congested unlicensed bands.

2.1.2 Discussion

In this section, we discussed that wireless *ad hoc* networks emerged as a solution for decentralized, flexible and scalable wireless networks, where devices communicate directly with each other. We further discussed the several types of *ad hoc* networks, specifically dedicated for a particular use case, that yet share many characteristics.

In this thesis, we intended to study wireless *ad hoc* networks formed by commodity devices. Thus, since leveraging licensed bands or acoustic communications require specialized hardware, not available in commodity devices, Cognitive Radio Ad Hoc Networks and UnderWater Networks are out of scope of this thesis. Regarding the other types, we decided to focus on generic wireless *ad hoc* networks since they abstract from the specific characteristics of each of the types discussed, i.e. some nodes may present mobility and devices are not heavily resource constrained. Note that this is not strictly a MANET, since we are considering mobility as optional, and is not strictly a WMN, since

[2] also known as Intermittently Connected Networks (ICNs)

we are not considering the network to be a communication backbone. Nonetheless, the solutions designed for these generic networks can then be transposed and optimized to any other type of wireless *ad hoc* networks.

In order to develop protocols and services for these networks, it is necessary to take into account the characteristics and challenges of the wireless medium, discussed next.

2.2 The Wireless Medium

The wireless medium is a shared medium through where devices communicate via radio waves with a given frequency. The majority of radio transmitters generate waves omnidirectionally, leading them to (potentially) reach all nodes within transmission range. Thus, when a node transmits a message, it is (potentially) received by all the nodes within its transmission range - its direct neighbors or neighborhood. This phenomenon is commonly referred to as *one-hop broadcast* [19, 97], and can be leveraged to devise *one-hop unicast* and *multicast* primitives, by having nodes, to which a message is not destined, ignoring it.

There are several technologies which enable forming wireless *ad hoc* networks. However, the majority of mobile commodity devices are only usually equipped with Bluetooth and WiFi (IEEE 802.11) antennas. Of the two, WiFi has the highest data rate and is fully decentralized (have no coordinators), allowing more flexibility. Therefore, we will focus on wireless *ad hoc* networks formed through the WiFi technology.

2.2.1 Wireless Communication Challenges

Due to the inherent characteristics of the wireless medium, wireless communications face many challenges, which are presented next.

Fading and Interference Since radio waves dissipate (lose energy) as they are propagated , the further away a receiver is from the sender, more difficult it has to distinguish between background noise and the sender's transmission (*Fading*) [60]. Obstacles may cause reflections, scattering, and refractions of electromagnetic waves, which usually lead to a given signal being transported by a multiplicity of indirect paths (*multi-path propagation*), that usually interfere with each other (due being slightly out of sync) [60]. The movement of the sender or the receiver(s) during the transmission of a message can cause the attenuation of the signal [60]. There may exist some other sources of electromagnetic *Interference* in the medium, which may overlap with messages' signals, leading to high levels of noise, which corrupt messages [60].

The measurement of the transmission power is called the Received Signal Strength Indicator (RSS or RSSI) [56, 60], and it can be used by a node to estimate its distance to the sender. For the same distance to the sender, over time and location, the RSSI may fluctuate around a given value, which may result in not all devices (at the same distance from the sender), receiving a given message.

Collisions and The Hidden Terminal Problem Since the wireless medium is shared among many devices (not necessarily from the same network), it is very frequent to happen multiple transmissions (with the same frequency) at almost the same time, overlapping their signals, leading those messages to not be received by none, or only a subset, of the devices within range [19, 60]. This phenomenon is called a *Collision* and directly detecting it, in the wireless medium, is impossible since the devices cannot transmit and listen, on the same frequency, simultaneously, because the strength of its own transmissions interferes with all the other signals. Thus, employing message recovery mechanisms is not a trivial task. *The hidden terminal problem* [19, 60, 114] is a particular case of collisions, that is very common in multi-hop wireless *ad hoc* networks. Suppose that a node **A** is reachable from two other nodes **B** and **C**, but those nodes are not reachable between themselves. When both **B** and **C** transmit a message at the same time, a collision happens between the two, making **A** unable to receive neither of them. In this case, **C** is a *hidden node* to **B** and vice-versa.

Contention and The Exposed Terminal Problem In order to prevent simultaneous transmissions, the nodes of a wireless network need to compete for the isolated usage of the wireless medium - *Contention*. This is employed through medium access control protocols, discussed in detail at Section 2.2.2. This might lead to *the exposed terminal problem* [19, 43, 114] which, in order to avoid collisions, a node decides to not transmit a given message, even if its transmission would not interfere with other ongoing transmissions, leading to a poor utilization of the wireless medium.

Repercussions into Wireless Networks The previous wireless medium problems can further cause additional problems at the network level, such as *Congestion*, *Unidirectional Links*, and *Network Partitions*. When there are many nodes competing to use the wireless medium (i.e. more contention), this can lead to nodes overflowing with messages to transmit, which is called *Congestion* [60]. The communication abstractions between nodes in transmission range, called (wireless) *links* can become very unstable, which may lead to *unidirectional (or asymmetric) links* [19, 72] [3]. The network can temporarily become fragmented into several subsets of nodes, called *Network Partitions*.

2.2.2 Wireless Medium Access Control (MAC) Protocols

Since the wireless medium is shared by multiple nodes, in order to avoid collisions and coordinate contention, Medium Access Control (MAC) protocols are employed, which

[3] This problem can also be caused due to nodes having different types of wireless antennas/receivers or different transmission power levels.

regulate its usage. Multiple MAC protocols have been proposed [21, 42, 54, 60], however we highlight the ones we consider most relevant: CSMA/CA, BMW, and TDMA.

Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) [60, 103, 111] consists in physically and virtually sensing the medium before transmitting, postponing transmission in case there is already an ongoing transmission. Virtually sensing is employed to mitigate the hidden terminal problem and consists in the receiver informing its neighbors that a transmission is happening, which they may be unable to directly sense. A number of enhancements to this protocol have been proposed in the form of other new protocols in MACA [43], MACAW [9], and FAMA [26], the latter being the predecessor of WiFi's MAC protocol [114]. An important aspect of this protocol is that unfortunately it only considers one-hop unicast messages, not employing any strategy to avoid hidden terminals in one-hop broadcast messages [97]. Furthermore, although the virtual carrier sensing seems to effectively solve the hidden terminal problem, this solution is not perfect since the power needed for interfering with a message transmission is much lower than the required for receiving it successfully. Consequently, hidden nodes may not be within the transmission range of the receiver [111], and thus not being informed of an ongoing transmission, and yet may still be able to cause interference.

Broadcast Medium Window (BMW) [94] protocol extends CSMA/CA to address the hidden terminal problem in one-hop broadcasts. For this, it requires every node to be aware of their one-hop neighborhood. For each message to be one-hop broadcasted, BMW assigns it a unique sequence number and selects one neighbor to execute regular CSMA/CA with. In this exchange, it is included in the message an interval of sequence numbers of previous transmitted messages, that have not yet been acknowledged by every neighbor. Before execting CSMA/CA, if the selected neighbor detects that it did not receive a previous message, it informs to sender to transmit it before the current message.

Time-Division Multiplex Access (TDMA) [10, 42, 54, 80, 113, 116] is a family of protocols that divide the time to access the wireless medium into frames, each composed by slots, usually of fixed size. In each frame, these slots are then assigned, or scheduled, to nodes links of the network, in a way such that all concurrent transmissions are (usually) guaranteed to be collision-free, and that each node can always transmit at least once (in a given frame). This assignment can be fixed, i.e. the same for every frame, or dynamic. When many nearby nodes transmit very frequently, TDMA prevents collisions from occurring and fairly divides the time between them. However, when only some nodes pretend to often transmit, TDMA leads to unnecessary delays in transmissions, deteriorating latency and throughput. A negative aspect of these protocols is that they either require a centralized entity [60], to coordinate the scheduling, or (usually) require that the nodes distributively maintain synchronization, another complex problem to solve in *ad hoc* networks [42, 86]. Furthermore, computing the optimal time slots is a NP-hard problem and approximations may lead to inefficient solutions [19].

2.2.3 Discussion

Even though MAC protocols try to mitigate (some of) the wireless medium problems, they usually are not enough to ensure that important messages are not lost and that nodes do not become congested. Therefore, the wireless medium's challenges should be taken into account when designing protocols and applications that leverage the wireless medium for communication. In particular, communication protocols for multi-hop *ad hoc* wireless networks may need to employ mechanisms to deal with collisions, contention, congestion, and some times, network partitions and asymmetric links.

The MAC protocol employed in WiFi is a variant of CSMA/CA, which does not provide any hidden terminal prevention mechanism for one-hop broadcasts, which is heavily leveraged in broadcast and sometimes in routing. Although in theory we could replace CSMA/CA with BMW or even TDMA, replacing the MAC protocol employed in commodity devices is not feasible, since it involves changing the communication stack, which is not always possible. Furthermore, it would turn the new stack incompatible with the standards. Nonetheless, application-level communication primitives may benefit from incorporating or adapting some techniques of some MAC protocols, such as BMW and TDMA, at the application level.

Now that we have discussed the problems inherent to wireless communications, we will review communication primitives for *ad hoc* networks, starting with the broadcast.

2.3 Broadcast on Wireless Ad Hoc Networks

Broadcast consists in delivering a particular message, sent by a single node - the *source*, to all nodes of the system [28]. In the case of *ad hoc* networks, the system is the whole network, being broadcast also usually called network-wide broadcast in the literature [92, 107]. For this, broadcast algorithms often leverage *one-hop broadcast* as a building block, to deliver a message to all direct neighbors, with a single transmission. It is important that the terms *one-hop broadcast* and *broadcast* are not confused, since they have different objectives.

The process of sending a message through broadcast is called broadcast process and it is usually spontaneous, being any node able to begin a broadcast process at any time [98].

Broadcast is a very important communication primitive in distributed systems [6, 24, 28, 32, 48, 101], specially in wireless *ad hoc* networks. Many protocols for *ad hoc* networks leverage on broadcast as a building block to, for instance, route discovery, topology information dissemination, geocast [4], create reputation systems, or distributed

[4] broadcast on a limited geografic area

caching [55, 56, 71, 107]. Consequently, improving the performance of broadcast can have a huge impact on many protocols for *ad hoc* networks.

However, devising efficient broadcast algorithms has many challenges, which are presented next.

2.3.1 Challenges of Broadcast in Wireless Ad Hoc Networks

During the propagation of a message, some nodes may perform redundant retransmissions, i.e. reach only nodes that have already received the message being transmitted. Furthermore, the neighbors of the nodes may attempt to retransmit at approximately the same time. Consequently, both of these phenomenons may lead to a high probability of having contention and collisions, which corresponds to the well-known problem of the *broadcast storm* [98]. There are two approaches to mitigate the *broadcast storm*: *i*) decrease redundant retransmissions, and *ii*) avoid simultaneous retransmissions of nearby nodes, by delaying each retransmission with a small random period.

Taking this into account, broadcast algorithms strive to simultaneously improve three distinct metrics: maximize their *reliability* while minimizing both their *redundancy* and their *latency*.

Broadly speaking, the *reliability* of an algorithm corresponds to its effectiveness in delivering all the messages to all nodes. Due to the inherent challenges of the wireless medium (previously explained in §2.2.1), guaranteeing that all nodes deliver a message is not simple, and employing strategies with retransmissions and explicit acknowledgments can easily lead to the saturation of the medium. Consequently, in wireless *ad hoc* networks, broadcast algorithms are usually *best effort* (or *unreliable*), i.e. there is no guarantee that all the nodes deliver all the messages. Thus, broadcast algorithms attempt to deliver a given message to the maximum number of nodes as possible, being that the higher its *reliability*, the better an algorithm is.

Furthermore, broadcast algorithms also make an effort to decrease its *cost*, which corresponds to the number of retransmissions performed to disseminate a message throughout the network. The lowest possible *cost*, while still reaching all nodes (*perfect cost*), corresponds to the size of the minimum connected dominating sets (MCDSs) of the network graph [18]. Thus, many algorithms attempt to distributively approximate a MCDS.

In addition to the two previous metrics, another important aspect in broadcast algorithms is minimizing the *latency* of each broadcast process [71], defined as the time required for all nodes to deliver a message (after the start of the broadcast process). Thus, the use of delays to avoid collisions has to be carefully configured, with the purpose of achieving the lowest *latency* without penalizing the *reliability*.

While trying to improve these three metrics, broadcast algorithms must have to take into consideration that there is a dependency between them [46] . To achieve an high *reliability*, an algorithm must avoid collisions, which is usually reflected by decreasing the *cost* or by increasing the random delays before transmitting (i.e. the *latency*). However, decreasing the *cost* too much, leads to a lower probability of a collision being compensated by a redundant retransmission and, in case the *cost* becomes lower than the *perfect cost*, reaching all the nodes becomes impossible, thus penalizing the *reliability*.

2.3.2 Classification of Broadcast Algorithms

Numerous broadcast algorithms have been proposed in the literature, which employ the most diverse techniques, to achieve the best performance under different scenarios.

To guide their decisions, both regarding the need to retransmit and computing a proper period to delay the retransmition, broadcast algorithms resort to several techniques which leverage multiple different types of information. As such, we grouped the most relevant types of information and classified broadcast algorithms according it. This classification, however, is not exclusive, being that the majority of existing algorithms employ and combine several techniques of different types.

- **Probabilistic**: Nodes can leverage probabilisties to decide to retransmit (or not) a given message. These probabilities can be static parameters [56, 85, 98] or can be dynamically computed by the algorithm [37, 56, 74]. Furthermore, broadcast algorithms can also leverage probabilities to compute the delays before retransmitting [98].

- **Counter-Based**: Several algorithms were proposed that resort to the number of copies received, either to influence the decision to retransmit [23, 51, 55, 56, 98, 108, 112] or to adjust the current retransmittion delay of a given message [37, 51, 88].

- **Hop-Count Aware**: This type of algorithms leverage the number of hops traveled by each copy of a message (until their reception by the current node), to influence the retransmition decision [34, 56, 88].

- **Position Aware**: Some algorithms resort to node's position information, either exact or relative to other nodes, to influence both the retransmition decision and the employed delay before retransmitting. This technique can be separated into two sub-groups:
  - **Distance Aware**: These algorithms take advantage of the relative distance between a node and its parents (i.e. the nodes who sent it the message) [13, 23, 49, 51, 55, 56, 98, 108], being that nodes usually retransmit if this distance is below or above a threshold, or compute a delay based on it (the distance). The distance can be estimated from the message's RSSI or calculated resorting to location systems, such as Satelite Navigation Systems (SNSs) (e.g. GPS).
  - **Location Aware**: When nodes are aware of their coordinates in a location system, they can perform more accurate estimations on the Expected Additional

Coverage (EAC), than resorting only to the distance. This technique is employed in [56, 93, 98, 115].

- **Energy Aware**: Some algorithms take into account the battery levels of nodes (when nodes are mobile), to attempt to minimize the network's overall energy consumption or individual nodes energy consumption during a broadcast process. Examples these strategies are select nodes with higher levels of battery to retransmit [90] or minimize node's transmission power [7, 13, 52, 106].

- **Neighbor Aware**: In some algorithms, nodes leverage network's topological information, to base their decisions. This topological information can either be global (e.g. [13, 52, 90]) or local (e.g. [50, 66, 67, 73, 92, 104, 106]), and it can be used to determine which nodes are the most suitable to retransmit or to compute the delay before retransmitting. Examples which leverage this information to compute the delay are [56, 66]. Regarding the decision to retransmit, these algorithms can be further separated into:

  – **Self Decision**: In this type of algorithms, nodes decide by them selves whether to retransmit or not a given message. Examples of this type of algorithms are [50, 66, 92, 115].

  – **Delegated Decision**: In some algorithms, each node does not decide by itself whether to retransmit or not, being this decision made instead by the node that sent them the message, i.e. its parent. Therefore, upon reception of a message, each node verifies if it has been selected by its parent to retransmit it. In case it was not, then the node just processes the message. Otherwise, the node must select a subset of its neighbors, to which it delegates the retransmission responsibility. There are many names in the literature given to this set of nodes, such as *forward lists* [50], *forward sets* [105], *multi-point relays (MPRs)* [15, 16, 73, 89], or *broadcast relay gateways (BRGs)* [67]. In order to simplify, in this thesis we decided to name it *delegated neighbors* of a given node. The *delegated neighbors* can either be: *i*) *static*, if they are independent of the messages, being the same for any message transmitted by a given node, in the case there are no changes on its neighborhood topology; or *ii*) *dynamic*, if they depend on the messages, being (potentially) different for each one. It is in the selection of the *delegated neighbors* that this algorithms differ, with several solutions proposed, such as [11, 17, 38, 50, 67, 73, 104] and [1, 15, 16, 75, 89, 105].

  – **Hybrid Decision**: In some *neighbor aware* algorithms, the decision of retransmitting a given message (or not) corresponds to a combination the two previous techniques [110], where nodes determine the need to retransmit of some of its neighbors and allow other neighbors to decide by them selves.

2.3.3 Broadcast Algorithms

Next, we will give concrete examples of broadcast algorithms, being that we selected those that we consider the most representative of the techniques previously presented.

Flooding [74, 88, 98, 107] is the most simple broadcast algorithm, where each node always retransmits each new received message. It can be considered as being a *probabilistc* algorithm, where nodes retransmit with 100% probability. Although being a simple and robust solution, it can incur in many redundant retransmissions (high *cost*) because all the nodes retransmit.

Gossip3 [56] is a variant of *Gossip*, a family of *probabilistc* broadcast algorithms, which employs a *counter based* mechanism to attempt to guarantee a successful propagation of messages, in regions of the network with low node densities. In this algorithm, every node retransmits each new received message with a given pre-configured probability. Optionally, nodes can wait a small random period before deciding to retransmit. For a given message, nodes who decided to not retransmit it, wait for an additional random period and then re-evaluate their initial decision. This re-evaluation corresponds to verifying if the total number of copies of that message received is below a given threshold. If it is, then the node retransmits the message, not retransmitting otherwise. Therefore, by employing this re-evaluation, *Gossip3* can force nodes in sparse regions of the network to retransmit, regardless of the pre-configured probability.

Hop Count-Aided Broadcasting (HCAB) [34, 56] is a *Hop-Count Aware* algorithm. Upon the reception of a new message, each node waits a random period. After this period timing out, nodes retransmit the message in case no copy was received, after the first reception, with an higher hop count (i.e. number of hops travelled). The intuition is that if a copy of a message is received with an higher hop count than the first, that message was already propagated through multiple directions, and thus the current node's retransmission has an higher probability of being redundant.

Power-Aware Message Propagation Algorithm (PAMPA) [23, 51, 55, 56, 108] is a family of *distance aware* broadcast algorithms. Of that family, we focus on the original algorithm [55], of where all the other variants derived from. In it, upon the reception of a new message, each node waits for a period proportional to the distance between itself and the node who sent it the message. Upon this period timing out, if the node received more copies (of that message) than a given threshold, it does not retransmit that message, doing it otherwise. Therefore, *PAMPA* gives priority on retransmitting to nodes farther way from their parents, and thus allowing closer nodes to receive more copies which potentially leads to them canceling their usually redundant retransmissions.

Scalable Broadcast Algorithm (SBA) [66] is a *self decision neighbor aware* broadcast algorithm, which requires each node to have neighborhood topology knowledge up to two hops. Each node, upon the reception of a new message, postpones the retransmission decision by a period inversely proportional to its number of neighbors. Then, upon this period timing out, the node checks whether its neighbors set is contained in the union of the neighbor sets of its parents. If this is the case, then all the node's neighbors were already covered (i.e. within transmission range) by a previous retransmission, and thus the node can abstain from retransmitting. The choice of a delay inversely proportional to the number of neighbors, gives priority in retransmitting to nodes with many neighbors, which generally leads to nodes with few neighbors receiving enough copies to cover their whole neighborhood, lowering the *cost* of the algorithm.

Lightweight and Efficient Network-Wide Broadcast (LENWB) [92] is also a *self decision neighbor aware* broadcast algorithm, which resorts to a system of priorities to verify if all the neighbors (of the current node) will be covered by future retransmissions of other nodes with higher priority. These priorities correspond to the number of neighbors (i.e. degree) of the nodes, being node identifiers compared for nodes with equal degrees. Therefore, this algorithm requires every node to be aware of its neighbors, its neighbors' neighbors, and the degrees of those nodes. Upon the reception of a new message, a node u first verifies if all its neighbors were already covered by its parent's retransmission. If that is the case, u decides to not retransmit. Otherwise, this algorithm makes u retransmit if all its neighbors are not covered by nodes with higher priority than itself.

Multi-Point Relaying (MPR) [17, 38, 73] is a *delegated decision neighbor aware* broadcast algorithm, which requires nodes to have two-hop neighborhood knowledge (considering only bidirectional links). In this algorithm, the *delegated neighbors* are called *Multi-Point Relays (MPRs)*, which are static, i.e independent of messages. Each node u computes its *MPRs* by computing a (approximate) minimum subset of its neighbors, which covers all u's two hop neighborhood. Then, upon u receiving a message, if it belongs to the *MPRs* of its parent, then it retransmits the mesage. Otherwise, u only processes the message, and abstains from retransmitting it.

2.3.4 Broadcast Frameworks

Many broadcast algorithms share certain architectural patterns, which led to the origin of different frameworks to simplify their specification. For instance, in [109] and [110] the authors present frameworks for specifying *neighbor aware* broadcast algorithms, either *self*, *delegated*, or *hybrid decision* variants. These frameworks identify the key aspects of these algorithms, which correspond to the decision to retransmit or not, which node makes that decision (self, delegated or hybrid), when that decision should be made (before receiving any message, after receiving the first copy, or upon some period) and what information this decision needs (neighborhood information up to some configurable amount of hops and priorities of nodes). Unfortunately, these frameworks are limited to a specific type of broadcast algorithms.

2.3.5 Discussion

In this section, we discussed a panoply of broadcast algorithms for *ad hoc* wireless networks, having many solutions been proposed that introduce or merge different mechanisms and techniques.

Position aware algorithms, although robust, require special features (Satellite Navigation Systems or access to RSSI) that are not available/accessible in several commodity devices. Furthermore, *energy aware* are also not suitable to be applied in commodity devices since not all these devices allow access to the battery level [5] or the accuracy of battery level measurements can be highly heterogeneous and imprecise. Therefore, in this thesis we will not focus on broadcast algorithms which employ those types of techniques.

Regarding the remaining types, on the one hand, *Counter Based*, *Hop-Count Aware* and *Probabilistic* techniques allow algorithms to deal better with networks' dynamism still, they overlook the topology, which impacts their performance on heterogeneous topologies.

On the other hand, *neighbor aware* broadcast algorithms enable taking into account heterogeneity in the network's topology and thus make better decisions regarding the need for retransmission. However, they require nodes to aggregate information about this topology, which may become stale with changes. The greater the dynamism of the topology, the worst these algorithms tend to perform.

Due to the highly dynamic characteristics of wireless *ad hoc* networks, adaptive solutions that switch or adjust the algorithm according to the localized characteristics of the environment, are the most suitable. In this sense, it is fundamental to understand how broadcast algorithms relate among each other, identifying which components they share and which are unique, so that we are able to easily compare and merge them. Thus, a framework that abstracts common aspects of broadcast protocols is a step in this direction. There are already some frameworks for broadcast algorithms. Nonetheless, they do not correspond to a completely generic broadcast protocol that captures the common aspects of all major broadcast protocols and that can be easily parameterized, to obtain a specific broadcast protocol, without major modifications to the already existing protocols.

2.4 Routing on Wireless Ad Hoc Networks

In a distributed system, nodes may only wish to communicate with a single node - *unicast*, instead of the whole system. In the case of wireless *ad hoc* networks, if the destination (of the message) is within the source's transmission range, the message can be sent directly

[5] e.g. a raspberry pi connected to a power bank

over the wireless medium. However, if that is not the case, the sender has to entrust to other nodes the responsibility of propagating the message to the intended destination, on its behalf.The simplest way to propagate the message is by broadcasting it, leading all other nodes to ignore it. Unfortunately, this is a very wasteful solution since it requires a great amount of retransmissions.To address this, whenever a node has a message to forward, it must able to determine to which of its neighbors it should send the message, so that the message can reach its intended destination (i.e. determine the *next hop*). Usually, routing algorithms store the *next hops* for each destination in a structure, called the *routing table*.

2.4.1 Challenges of Routing in Wireless Ad Hoc Networks

Due to the characteristics of *ad hoc* multi-hop wireless networks, the process of determining routes is not trivial. In the first place, contrasting with wired networks, the topology of wireless *ad hoc* networks is more dynamic due to a higher possibility of occurring failures, both of nodes and links, as well as the potential node mobility. For this reason, routing algorithms for wireless *ad hoc* networks must be able to rapidly adjust to topology changes. At the same time, a high number of control messages, even if small in size, can saturate the wireless medium. Hence, routing algorithms must also attempt to minimize their control traffic overhead. Therefore, it is highly complex to efficiently build a virtual structured network topology (i.e. *overlay*) to achieve efficient routing, due to the overhead of maintaining these structures.

Furthermore, routing algorithms must also avoid the formation of routing loops, deal inconsistent and stale topological information, and be aware of the existence of unidirectional links.

As a result, the existence of many rivaling objectives is in the genesis of several different routing algorithms that strive to address these challenges.

2.4.2 Classification of Routing Algorithms

The main classification criteria for routing algorithms is the availability of routes, which classifies each algorithm into:

- **Proactive (or table-driven)**: *a priori* computes and maintains routes to all destinations so that when they are needed, they are immediately available. This means that these algorithms must actively maintain routing tables up to date, which is usually achieved by periodically broadcasting control information (high overhead). Unfortunately, if the network topology changes very often, it becomes quite difficult to keep all routes up to date and, if the network activity is low, most routes may not even be used. Furthermore, since each node maintains routes for each possible destination, which are difficult to summarize, these algorithms are usually not scalable. Examples of this type of algorithms are [25, 27, 31, 36, 38, 39, 59, 65, 84, 99].

- **Reactive (or on-demand)**: compute routes to destinations only when they are required, searching the network via broadcast. In this way, these protocols avoid wasting computational resources in maintaining routes that are not used and, at the same time, also decreasing the amount of information that each node has to keep at each moment. However, when the network topology is very dynamic, routes are constantly being broken, which leads to many consecutive searches. Furthermore, these protocols also incur in a high initial latency due to the search for the route. Examples of this type of algorithms are [14, 40, 44, 69, 79, 91].

- **Hybrid**: seek to merge the best of the previous approaches, by maintaining some routes proactively, and others reactively. Examples of this type of algorithms are [29, 61, 76].

According to the nature of the *next hop* selection, routing algorithms can be classified into:

- **Distance Vector**: nodes exchange the relative distances they are regarding the destinations and then assign as next-hops those neighbors that are closer to the destination. Examples of this type of algorithms are [31, 69].

- **Link State**: each node acquires global topology knowledge and locally computes the best path to each destination, thus being able to identify the most suitable next-hop. Examples of this type of algorithms are [27, 38, 59, 99].

- **Link Reversal**: to each link is assigned a logical direction. Route computation consists in reversing the logical direction of links between neighboring nodes. The resulting virtual topology corresponds to a Directed Acyclic Graph (DAG), oriented towards the destination. A node determines the *next-hop* as any neighbor at the outgoing logical extremity of its links. Examples of this type of algorithms are [61].

According to the method of dissemination, routing algorithms can be further classified into:

- **Non-opportunistic (or uni-path)**: has each node selecting a specific neighbor as the next hop to forward the message to. Examples of this type of algorithms are [38–40, 69].

- **Opportunistic (or any-path)**: leverages the broadcast nature of wireless communications to select multiple neighbors as the potential next-hop, called *candidates*, that must coordinate between themselves to determine who will forward the message. Therefore, these algorithms dynamically determines a route towards the destination, which allows to quickly mitigate failures in wireless communications. Examples of this type of algorithms are [84].

According to the determination of the route a message travels to reach the destination, routing algorithms can be classified into:

- **Source Routing**: for each message, the sender node specifies, in the header of the message, the route, complete or partial, that the message has to travel, in order to reach the destination. Examples of this type of algorithms are [40].
- **Non-Source Routing**: each node only chooses the next-hop, being the route determined by all the nodes that forwarded the message, instead of being determined only by the sender. Examples of this type of algorithms are [27, 38, 39, 69].

Routing algorithms can also be classified according to the type of Quality of Service (QoS) they strive to achieve, i.e. the type of metric(s) they pretend to maximize or minimize, being classified into:

- **Latency (or Hop-Count) Based**: Attempt to minimize the end-to-end delay of messages transportation. Usually this is done by minimizing the number of hops of each route. Nonetheless, other aspects can have an impact on latency as well. Examples of this type of algorithms are [27, 31, 38, 40, 69].
- **Throughput (or Link Quality) Based**: Attempt to guarantee a certain minimum throughput of the routes, by selecting the intermediate links with the highest bandwidth and highest probability of successfully forwarding messages (i.e. less collision and interference probability). When retransmissions are employed to reinforce the propagation of a message, the higher the link quality, the lower the latency. Examples of this type of algorithms are [39].
- **Stability (or Availability) Based**: Attempt to maximize the duration (life-span) of a route, i.e. minimize the amount of route/link breaks. The less the number of route breaks, the lower the latency.Examples of this type of algorithms are [96].

2.4.3 Routing Algorithms

Next, we will give concrete examples of routing algorithms, being that we selected those that we consider the most representative of the techniques previously presented.

Optimized Link State Routing (OLSR) [17, 38] is a link state proactive routing protocol that provides optimal routes regarding the number of hops. In this algorithm, each node u computes a (approximate) minimum subset of its neighbors, which covers all u's two hop neighborhood, called its *MPRs* (this is the same set computed in the *MPR* broadcast algorithm, previously discussed in §2.3.3). Then, each node informs its neighbors of the computed *MPRs*. After everynode exchanging their *MPRs*, the nodes are able to determine which of its neighbors selected them in their *MPRs*. This subset of neighbors is called the *MPR Selectors* of the node, and it is periodically broadcast by every node resorting to the *MPR* broadcast algorithm (previously discussed in §2.3.3). Each node by broadcasting the *MPR Selectors* instead of the complete neighbor set, enables *OLSR* to reduce the amount of information disseminated. Through the *MPR Selectors* received, each node then constructs a graph from which they compute the optimal path towards all destinations.

Better Approach to Mobile Ad hoc Networking (BATMAN) [39, 58] is a very simple proactive routing algorithm. In this algorithm, each node periodically broadcasts a control message, named *originator message (OGM)*, which contains a unique sequence number (monotonically crescent). When a node has a message to forward, it determines the *next-hop* as being its neighbor which received more *OGMs* from the destination node, in the current sliding window (i.e. range of sequence numbers).

auto-adJustable Opportunistic acKnowledgment/timEr-based Routing (JOKER) [84] is an opportunistic proactive routing protocol inspired by *BATMAN*. It improves *BATMAN* by dynamically adjusting the broadcast time interval of *OGMs*. Since *JOKER* is an opportunistic algorithm, it forwards any message to multiple potential *next hops* - the *candidates*. The criteria to select neighbors as *candidates* is to select the most distant ones (resorting to the RSSI) with the highest link quality (i.e highest sucessfull message transmissions over that link). In each message, the *candidates* are piggybacked in the header. *JOKER* defines two types of *candidate coordination*: *i*) *ACK-based* where *candidates* upon receiving a message to forward, send an acknowledgment (ACK) to the parent that sends a notification to forward to the node who sent the first ACK. *ii*) *Timer-based* where *candidates* upon receiving a message to forward, wait a period proportional to their priority, having the one with highest priority immediately forwarding. While waiting, the others listen to the medium for copies of the message and if no copy is received, they forward it.

Dynamic Source Routing (DSR) [40] is a reactive source routing algorithm where each node creates and maintains a cache of known routes - *route cache*. When forwarding a message, the source node first consults the *route cache* to verify if there is a known route to the destination. If there is not, then the node starts a *route discovery* to find it: *i*) first, the source node broadcasts a *route request* message. *ii*) upon this request being received by the destination, then it sends the path propagated by the message, from the source to the destination, through a *route reply* message, through the path: *a*) if only bidirectional links are being considered, send through the inverse route. *b*) otherwise, it may have to resort to a different path. Thus, it verifies if it has a route in its *route cache* and if not, it broadcasts a *route request* for the source, on which it piggybacks the route to it. After obtaining a route, then the node inserts it in the header of the message, and forward the message to *next hop* in the route.

Ad hoc On-Demand Distance Vector (AODV) [68, 69] is a reactive routing protocol where each node maintains a table with an entry for each destination. Apart from the destination's address, each entry also contains the neighbor's address to which a message for that destination should be forwarded (next hop) and a list of neighbors that use the current node as the next neighbor for that destination (predecessors). Each entry also has an associated validity time which is refreshed whenever the route is used.

When a node needs a route to a new destination, it broadcasts a request. Every node that receives this request, creates an entry in the routing table, with the source as the destination and with its parent as the next hop. When this request is received by a node that knows a fresh route to the destination or is the destination, it then sends a reply through the reverse path the request traveled. Along this path, each node inserts in the predecessors' list, of the destination's entry of the routing table, the address of the next hop of the reverse path.

If the source wants to establish a bidirectional connection with the destination, i.e. the destination also has to know a route back to the source, the request has to have the "gratuitous reply"flag set. In the case an intermediate node responds to the request instead of the destination and this flag is set, the node also has to send a gratuitous reply to the destination.

Additionally, each node monitors the link state with their neighbors. Whenever a link breaks, i.e. a neighbor is lost, the current node sends an error message to the nodes belonging to the predecessors list of all the active entries of the routing table that had the lost neighbor as the next hop. This error message is the propagated until it reaches the source node.

Associativity-Based Routing (ABR) [96] leverages the duration of neighboring links, called *associativity ticks* as a metric to determine the most stable routes between nodes. Thus, upon the reception o a route request, the destination chooses the route with the highest *associativity ticks*, using the hop number to break ties. Consequently, the selected routes are prone to break less frequently.

Zone Routing Protocol (ZRP) [29, 30] was the first hybrid routing protocol.

In it, each node as an corresponding *routing zone* that includes all the nodes at most *zone radius* away form it. Within the zone, nodes run proactive protocol, having knowledge therefore of the network's topology within the zone. To find destinations outside their zone, nodes run a reactive protocol. Since the zones overlap, this protocol tends to be extremely robust.

When a node wants to send a message, it first verifies it the destination is not within its *routing zone*. If it is, then it knows a full path to it and can forward the message. Otherwise, it sends a query to all the nodes on the periphery of its *routing zone*. Each of these nodes then repeat the process until the destination is found. When this happens, a reply is sent to the source containing all the peripheral nodes that forwarded the query.

Therefore, the routes are a sequence of nodes *zone radius* hops awya from each other. Consequently, these routes are more stable than full routes and it can provide multiple paths to the destination.

In order to find optimal values for the *zone radius*, there are somo proposed methods [64, 83] that dynamically find it based on network load, mobility, and the frequency of link-failures.

Temporally-Ordered Routing Algorithm (TORA) [61, 62] is an hybrid link reversal algorithm.

It leverages a global clock (physical or logical) to establish the temporal order of topological change events, used to order the algorithm's reaction to topological changes. Unfortunately, having a synchronized global clock in a real distributed system, especially in ad hoc networks, is problematic. Nonetheless, this algorithm suggest an interesting approach and should therefore be considered.

TORA aims at reducing the overhead in reacting to changes on the network's topology, by affecting only a localized small sub-set of nodes, while guaranteeing all routes are loop-free. For this, nodes only need to maintain information about their direct neighbors.

For each destination, a separate version of the protocol must be run. Each node as an associated value, named its *height*, that is composed by a *reference level* and an offset (in reality it is a quintuple, being each of these components separated into sub-components). The values of all nodes are totally ordered. This heights are used to determine the "virtual"direction of each bidirectional link, being directed from the higher node to the lower. The link's labels can be: *i*) *undirected*, when there is no known route to the destination, *ii*) *upstream*, when the current node's height is smaller than its neighbor's height, or *iii*) *downstream*, when the current node's height is larger than its neighbor's height. Creating routes consists in assigning direction to links.

When a node without directed links requests a route to a given destination, it broadcasts a query. Upon the query reaching the destination, an height determination process begins expanding from this node. This process creates routes towards the destination, by establishing a sequence of directed (*upstream* or *downstream*) links, which results in a Directed Acyclic Graph (DAG), directed to the destination. Therefore, typically provides multiple routes for the same source to any destination and any node can reach it. Unfortunately, this makes all the nodes to participate in all the active routes, even the ones not interested in communicating with the destination.

After the DAG being established, for a message to reach the destination, it just has to be forwarded along *downstream* links.

Whenever a node, other than the destination, ends up with no *downstream* link due to broken links, the node reverts all its links by incrementing its *reference level*, which consists in determining a new global maximum height for itself. Then, if any other node ends up with no *downstream* link due to this, it does a partial reversal of its links. In the case of the detection of a network partition, all links in the fragment of the network that became partitioned from the destination, must be *undirected* to erase invalid routes.

Sharp Hybrid Adaptive Routing Protocol (SHARP) [76] is an hybrid algorithm that automatically determines the perfect equilibrium between proactive and reactive behavior and enables each destination to used a different metric to optimize the routing to itself.

It maintains *routing zones* only around nodes that are popular destinations and, within this zones, the routes are only proactively maintained to the center node through an optimized version of *TORA*. To find destinations to which a node is not within the *routing zone*, *AODV* is used.

Each node measures the characteristics of the traffic and the network and use it to compute the optimal radius value for it self, independently of the other destinations, employing the metric it wants to optimize.

2.4.4 Routing Frameworks

Many algorithms share architectural patterns, which leads to the origin of different frameworks to simplify their specification.

In [82] the authors present a framework for specifying hybrid algorithms, where the routes maintained proactively are to nodes within a circular routing zone with a radius independent for each node, that is adjusted dynamically. Unfortunately, it does not fully abstract the common aspects to both reactive and proactive protocols, providing only a way to hybridize them, by selecting the one (reactive or proactive) that should be employed to find/maintain the route to a given destination. Moreover, it only supports proactive circular zones, which is what most hybrid algorithms do, however it is somewhat restrictive if future solutions arise that want to proactively keep routes in non-circular zones. Furthermore, it also requires the modification of pure proactive protocols, for nodes to maintain only information inside of the routing zone.

In [95] is presented a framework that abstracts each routing protocol into three modules that create, maintain, or disseminate control messages over multiple distributed structures called RNS. However, it only generalizes the dissemination of control messages of routing protocols, leaving out other relevant aspects for the functioning of a routing protocol, such as the common patterns in the processing flow of data messages (e.g. obtain the next hop for a message). Additionally, the conversion from a specification of an algorithm to an implementation/specification in this framework can be non-trivial.

2.4.5 Discussion

As discussed in this section, the literature on routing algorithms for wireless *ad hoc* networks is rather extensive, existing many algorithms which employ the most diverse techniques to route messages to their destination.

Hierarchical algorithms although quite efficient in reducing the amount of information each node has to maintain, incur in high overhead in maintaining the hierarchical structure and therefore we will focus our attention on flat algorithms. Opportunistic strategies can be combined with other algorithms to improve their reliability in propagating messages to their destination. Similarly to broadcast, we decided not to consider algorithms that leverage on distance, location, and energy information, since they require special features that are not available/accessible in the generality of commodity devices.

Regarding the availability of routes, on the one hand, proactive algorithms are best suited for small networks where nodes want to communicate with all destinations. However, the amount of information that each node has to maintain is proportional to the number of nodes in the network, so these solutions are often not scalable on the size of the network.

On the other hand, reactive algorithms are more adequate to larger networks, when only a few destinations are needed (for each node), since they require information to be maintained only by active routes. Nevertheless, they suffer from the latency and message overhead in establishing routes prior to communicating and, in large networks with heavy traffic patterns, simultaneous route discoveries can lead to broadcast storm [70].

In turn, hybrid algorithms strive to achieve the best compromise between the amount of routes that are proactively maintained against routes that are established only when needed. Furthermore, due to the highly dynamic characteristics of these networks, adaptive solutions that switch or adjust the algorithm according to the localized characteristics of the environment, are the most suitable. In this sense, like in broadcast, it is of utmost importance understanding how the different solutions relate among each other so that better hybrid algorithms can be devised. Thus, a framework that abstracts common aspects of routing protocols is a step in this direction. There are already some frameworks for routing algorithms. Nonetheless, they do not correspond to a completely generic routing protocol, that captures the common aspects of routing protocols and that can be easily parameterized, in order to obtain a specific routing protocol, without major modifications to the already existing protocols.

2.5 Summary

We started this chapter discussing wireless networks, highlighting the characteristics, fundamental concepts, and existing types of wireless *ad hoc* networks. We decided to focus on generic wireless *ad hoc* networks since they are the most suitable to be formed by commodity devices.

With the purpose of developing communication primitives for these networks, we delved into the characteristics and challenges of the wireless medium and reviewed some solutions to mitigate them - MAC protocols. We also reviewed some of the most relevant wireless technologies that enable to form wireless *ad hoc* networks, and picked WiFi since is the most common and with highest data rate on commodity devices. Although we are not allowed to change the default MAC protocol of WiFi (CSMA/CA), some mechanisms and techniques of other MAC protocols can be leveraged at the application level to increase the robustness of communication primitives.

Afterwards, we studied the broadcast problem in wireless *ad hoc* networks, and presented a vast amount of algorithms proposed over the years. We decided not to consider distance, location, and energy aware algorithms since they require special features that are not available/accessible in the generality of commodity devices. We pointed out that it is fundamental to understand how broadcast algorithms relate among each other, in order to devise better algorithms.

Finally, we addressed the routing problem in wireless *ad hoc* networks, and reviewed the most distinguished solutions of the literature, and concluded with the observation that, like in broadcast, it is highly important to understand how the different solutions relate among each other so that better algorithms can be conceived.

Chapter 3

Planning

We start this chapter by presenting an overview of our current prototype for a broadcast framework (§3.1). Next, we introduce the methodology to create a routing framework (§3.1). We continue by presenting the experimental evaluation plan and the selected metrics to evaluate (§3.3). Finally, we conclude the chapter with the schedule for the work to be developed in the remaining of this thesis (§3.4).

3.1 Broadcast Framework

At the time of writing, we devised a conceptual framework which captures the behaviors of broadcast algorithms, which were presented in Section 2.3.3. This framework corresponds to a generic broadcast protocol, which can be parameterized to specify exiting protocols/algorithms. A preliminary version of the framework was published in SRDS 2019 [81]. Due to lack of space, we omit the details of this framework from this document.

Leveraging this framework, we intend to devise better adaptive algorithms, capable of adapting their behavior and/or fine-tuning their parameters according to the execution environment. To do this, we will start by performing an extensive experimental evaluation on the most relevant algorithms found on the literature, in multiple different topologies. Next, taking into account the results obtained in this evaluation, we will identify the settings where each algorithm performs better (or worse) and then apply adaptative techniques to improve the robustness of adaptive algorithms. Finally, we intend to evaluate the performance of such adaptive algorithms against existing solutions.

3.2 Routing Framework

Similar to what we did for broadcast, we intend to develop a generic framework that abstracts the common aspects of the routing protocols and converts the particular behaviors of existing protocols. However, unlike broadcast algorithms, the execution flow of routing algorithms is much more heterogeneous. Hence, firstly we will try to formulate a framework for specifying proactive routing algorithms, starting by comparing the execution flow of the most relevant algorithms and attempting to generalize those flows. Next, we plan to use the same principle to create a framework for reactive routing algorithms. Finally, we plan to unify the two frameworks, in order to obtain a generic routing framework, capable of specifying any type of routing algorithm, either proactive, reactive or even hybrid.

Then, leveraging this framework we intend to devise better adaptive hybrid algorithms, capable of changing their behavior and/or fine-tune their parameters according to the execution environment.

3.3 Evaluation

We intend to experimentally evaluate our work in a real *ad hoc* network, formed by twenty four Raspberry Pi 3. Regarding broadcast algorithms, we will evaluate them resorting to the previously discussed metrics: *reliability*, *cost*, and *latency*. Regarding routing algorithms, we will evaluate them resorting to their *reliability*, *overhead*, and *latency*. The *reliability* of a routing protocol is defined as the fraction of successfully delivered messages over the total number of messages sent (only data messages are considered). The *overhaed* is defined as the fraction of control messages over the total messages sent (control messages + data messages). The *latency* is defined as the delay between the moment a message is sent to the moment it is delivered by the destination. Only messages successfully delivered are considered.

We intend to perform three types of experiments:

- **Topology**: Evaluate the performance of the algorithms against different topologies. In these tests, apart from test the same topology through an experiment, we intend to have a set of dynamic topologies tested with node and link failures and recoveries.

- **Flow**: We also intend to evaluate it according to different levels of simultaneous messages being broadcasted/routed at the same time by many nodes. The higher the amount of messages, the more likely it is for collisions to happen. We want to measure the impact of these collisions across different protocols.

- **Mobility**: If possible, we also intend to evaluate the performance of the algorithms against different levels of node mobility. The main challenge here is controlling the mobility of a device in a repeatable way.

3.4 Scheduling

We have organized the work to be conducted towards the completion of this thesis in the following tasks, which are scheduled as denoted on Figure 3.1:

- **Task 1**: Broadcast Framework Development
  - **Task 1.1**: Optimize and extend the current prototype
  - **Task 1.2**: Implement more broadcast algorithms
  - **Task 1.3**: Devise adaptive broadcast algorithms
- **Task 2**: Routing Framework Development
  - **Task 2.1**: Develop framework for proactive routing protocols
  - **Task 2.2**: Develop framework for reactive routing protocols
  - **Task 2.3**: Unify the two frameworks and implement
  - **Task 2.4**: Implement Routing algorithms leveraging the framework
  - **Task 2.5**: Devise adaptive routing algorithms
- **Task 3**: Experimental Evaluation
  - **Task 3.1**: Preliminary experimental evaluation of broadcast protocols
  - **Task 3.2**: Full evaluation of adaptive broadcast protocols
  - **Task 3.3**: Preliminary experimental evaluation of routing protocols
  - **Task 3.4**: Full evaluation of adaptive routing protocols
- **Task 4**: Thesis Writing
  - **Task 4.1**: Paper with the extended broadcast framework and adaptive broadcast algorithms
  - **Task 4.2**: Paper with the routing framework and adaptive routing algorithms
  - **Task 4.3**: Thesis Writing

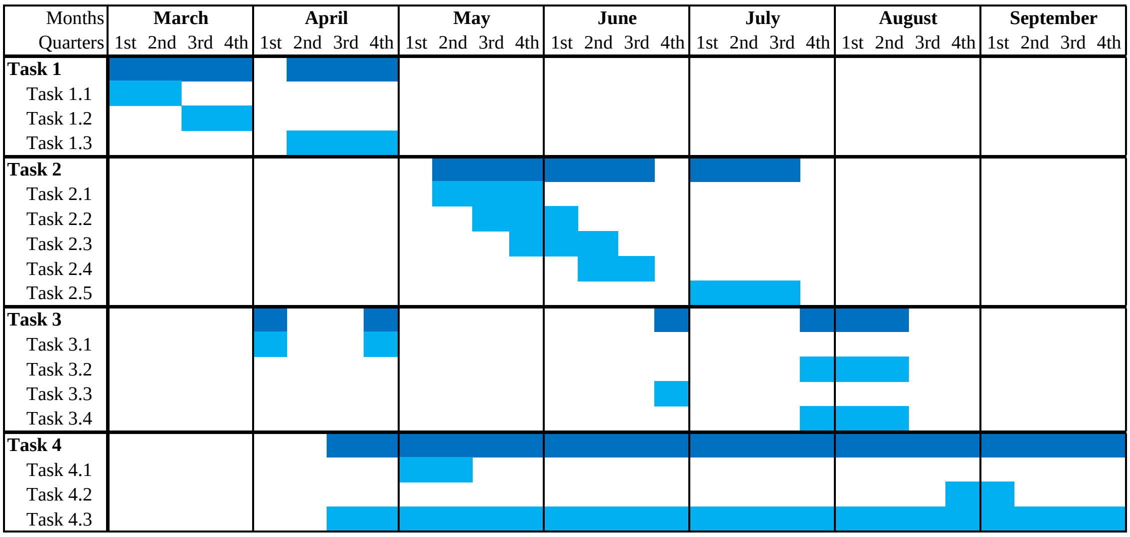

Figure 3.1: Work Plan

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