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Medium Access and Efficient Use of Multihop Wireless Networks

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UNIVERSITÉ DE STRASBOURG

École doctorale MSII

Medium Access and Efficient Use of Multihop Wireless Networks

DISSERTATION

submitted in partial fulfillment for the degree of

Habilitation from the University of Strasbourg

(computer science)

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by

Fabrice Théoleyre

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Avant-Propos

Writing an *habilitation à diriger des recherches* is always a complicated task. Some of us choose to present their vision of a whole research domain, to extract the structuring topics, and the associated scientific problems to study in the next years.

I rather chose to present a critical panorama of the research topics I conducted for the last 7 years. My objective consists in presenting the key aspects of my propositions, and more importantly to present their limits, seldom studied in the scientific literature. I tried to present a critical but constructive view, to give some perspectives in order to improve the propositions described in this manuscript.

I chose in this manuscript to present only a very limited part of the related work, in the course of the manuscript. Indeed, a detailed description of the whole related work seems for me out of the scope of an habilitation.

The governing thread of all my work explores distributed algorithms and protocols for multihop wireless networks. I focused mainly on medium access: in both wireless sensor and mesh networks, challenges look very similar. Adopted solutions are often very comparable, even if wireless sensor networks obviously are also energy constrained. Since medium access should not be considered in isolation, I also studied how a network may exploit efficiently this medium access: how may we construct for instance efficient routes above these improved MAC layers?

The work I developed with all the researchers who have accepted to collaborate with me revolves around 3 major topics:

1. the organization of transmissions in the MAC layer with an accurate topology control solution;
2. using multiple channels in parallel to solve the problems created by multihop topologies;
3. the joint MAC / routing optimization.

Chapter 1

Introduction

This document presents an overview of the research I conducted since my PhD defense, in 2006. My interests mainly focus on wireless multihop networks. I tried to adopt both a theoretical and practical approach. These research activities first took place in the Laboratoire des Systèmes et Réseaux (**LSR**) in Grenoble as a postdoctoral fellow, then in the Laboratoire Informatique de Grenoble (**LIG**, ex. LSR) as a CNRS research scientist. Finally, since 2009, I am a research scientist in the laboratoire des sciences de l'Ingénieur, de l'Informatique et de l'Image (**ICUBE**, ex. LSIIT).

1.1 Applications & Context: from ad hoc to wireless mesh and sensor networks

During my PhD, I mainly studied mobile ad hoc networks (MANets), proposing self-organization solutions to solve the routing problem. Mobility is very complicated to be taken into account: a radio link may appear and then break very quickly. The dynamic topology makes the design of algorithms very complicated. Indeed, it is difficult to propose solutions working efficiently in most situations, without any possibility to predict how each node behaves and moves.

Since my PhD, I focused on two major applications of the wireless multihop networks:

mesh networks : a collection of wireless routers have one or several radio interfaces and are in charge of relaying the packets toward a few gateways, interconnected to the Internet. A mesh network should support throughputs of a few megabits per second, with for instance multimedia flows. They would be particularly helpful to deploy quickly autonomous wireless multihop networks, non controllable, non censurable, such as described in the press [Atl13]. These networks are also deployed to offer a wireless connectivity in urban environments such as Freifunk.net covering german cities [Fre]. The community urban mesh networks have even their dedicated conference [Is4]. Commercially, Meraki (part of Cisco since 2012) deploys multihop Wifi [Mer].

sensor and actuator networks are constituted by low cost devices, with a single radio interface to send measures and receive commands. To reduce the costs, each node serves also as wireless router toward the gateway nodes (often designated as sinks, collecting the measures of sensors). An important focus is given to the network lifetime (a node with a battery should operate properly during several months / years) to the detriment of throughput (the radio bandwidth is typically under a few hundreds of bits per second).

During several years, a collection of proprietary solutions have emerged: they are not interoperable. For a few years, we note a convergence toward the all-IP networks. The new Internet of Things aims at integrating smart objects while guaranteeing an IP connectivity and thus inter-operability. The IETF working groups such as 6LoWPAN [6Lo], Roll [rol], and 6tisch [6ti] fall fully within this trend. They

reflect the interest of academic and industrial researchers in this topic. We may also consider mesh networks as a backbone network to collect the traffic coming from the Internet of Things. *Bubbles* of sensors and actuators may be interconnected through a mesh network.

While these topologies are static (i.e.the nodes are not mobile), the scientific challenges to solve are greatly sufficient to justify this research topic. During the last years, I tried to address a few of them.

1.2 Challenges of multihop wireless networks

Multihop wireless networks have attracted much attention since the design of an all-wireless network by the DARPA (PRNET) [JT87]. This class of networks has been nowadays declined into mobile ad hoc, hybrid, mesh and sensor networks.

However, some challenges remain still open. I will detail here some of them, denoting their specificities.

1.2.1 Asymmetrical view

In a wired network, a link is a physical cable linking the emitter and the receiver (optical fiber, copper wire). When the medium is shared, the MAC protocols assume that all the receivers and emitters have the same view of the activity (possibly shifted in time). In conclusion, any receiver detects the collision, and have the same landmarks on the radio activity.

This axiom does not hold anymore in wireless multihop networks: two emitters which do not hear each other may create interference and collisions in the two associated receivers. This situation leads to unfairness [Cha+05].

This asymmetrical view is even amplified by some techniques to make the radio link *robust*. Transmitting a packet with a low bitrate (with a different modulation) or using a larger transmission power improves the packet delivery rate. However, it may create indirect problems such as the performance anomaly: even in a cellular network, when all the emitters do not use the same modulation, the global throughput is limited by the weakest station [Heu+03].

1.2.2 What is a radio link?

We use commonly the concept of *radio link* to describe a possibility of communication between two terminals. However, this concept hides several problems we should keep in mind:

a radio link has often a quality: a packet transmitted by a node may not be decoded by the receiver. We often translate this radio link quality by a packet delivery rate, metric used for instance to select the most efficient routes [DC+03]. In other words, a radio link has not binary existence, impacted as explained previously by the transmission power, the modulation, the location of the nodes, etc.

asymmetry: because of the radio channel reciprocity, a link should be symmetrical. However, interference sources or different transmission powers (badly chosen, or part of the hardware inaccuracy) may for instance create asymmetry. In such situation, how should we use a radio link when the inverse direction is not available or presents a second-rate quality? Most of the MAC protocols require for instance and acknowledgment, this type of link being complicated to exploit efficiently.

Liu and Liao have highlighted the asymmetry may come from imperfect bandpass filters [Liu+08]. However, to the best of my knowledge, the inaccuracy of other radio chipsets has not yet been investigated.

what is a neighbor? traditionally, we consider a neighbor is a node with which we may exchange packets. However, is an asymmetrical neighbor a neighbor? In the same way, where is the threshold below which we consider a node cannot be anymore considered as a neighbor? a packet delivery ratio of 99%, 90% or 30% ?

In most cases, the neighbor concept is intrinsically linked with the protocol exploiting the topology: what characteristics are required for the protocol to work properly? In conclusion, the notion of neighbor is often relative and not anymore absolute.

We must in conclusion design algorithms and protocols exploiting efficiently the radio network, despite its complexity.

1.2.3 Conditions variability

A multihop wireless network undergoes continuous variations, even if the nodes themselves are static. The RSSI metric, denoting its radio link quality, may vary significantly over time [Cer+05a] because of activity (mobile obstacles), air humidity (in a field with a CC1100 radio chipset) [TG05], or even because of other unidentified factors.

This is practically complicated to operate efficiently this kind of networks. While we may choose to use only radio links with stable conditions, Alizai et al. have proposed an opportunistic approach [Ali+09]. An intermediary node which detects it has a good radio link quality may propose to relay temporarily the packets. As soon as a packet is not delivered, the emitter retransmits it directly to the original destination, bypassing the intermediary node.

1.2.4 Broadcast medium

Radio transmissions consist in a broadcast signal by nature: the signal may be received by all the nodes in the vicinity, whatever they are (receivers, emitters, idle). Filtering in the MAC layer allows the nodes to receive only interesting frames. This broadcast property has some consequences:

natural broadcast: many protocols rely on broadcast (diffusion to any receiver) to flood some information in the vicinity. However, this flooding may create collisions. Besides, such transmission is unreliable because of the radio link quality and its variability, has exposed previously. Thus, algorithmic and protocolar mechanisms have to be set up to implement a reliable diffusion mechanism [Ni+99].

However, this property is interesting to disseminate control information with a minimum cost for the emitter. We may use for instance intensively the *piggybacking* technique [Hua+11].

over-listening: a node consumes energy to receive and decode a packet, even if the MAC layer filters and drops it. This *over-listening* problem is particularly important in energy constrained networks.

1.2.5 Fairness versus Throughput

We must often face to two antagonist objectives:

Global throughput: the objective consists in maximizing the global aggregated throughput. In a convergecast network (where each packet must be collected by the sinks), the objective consists in maximizing the number of packets received by the sinks.

Fairness: in most cases, maximizing the throughput implies that some nodes receive a null bandwidth. In convergecast network, single hop transmissions tend to be privileged, dropping the packets coming from nodes farther from the sinks. In other words, neighbors of the sinks receive often a larger bandwidth. Such drawback is clearly unacceptable in most applications.

This is often complicated to define fairness: should we guarantee a bandwidth per flow, per emitter, or per hop? This fairness may even be proportional to the generated traffic, or to the radio ressource consumed by the flow.

1.2.6 Energy

Finally, we have to address the energy efficiency problem. In a wireless sensor/actuator network, we must guarantee the network operate properly during a minimal duration. This **network lifetime** may be upper bounded by the death of the first node, or by the date at which the service is not anymore insured [DD09].

Recently, the energy constraint has been studied in classical networks. For instance, Ethernet networks are destined to be more thrifty in energy with the standard IEEE 802.3az [Chr+10]. In the same way, some researchers have studied the energy problem in wireless mesh networks [Cap+12] or mixed optical/radio networks [Cho+10].

1.3 Manuscript organization

I mainly focused on the medium access for multihop wireless networks. How does a collection of nodes may share the medium access while reducing the number of collisions, the idle time, and guaranteeing a given fairness? I also wanted to go further, by focusing on the construction of efficient routes. Indeed, for me, both problems are intimately related: the roles of medium sharing and route construction cannot be so clearly separated in disjoint and independent layers. As I will expose in this manuscript, a perfect layer independency damages significantly the global performance of a multihop wireless network.

I chose to structure this manuscript in three main chapters, and I don't follow a division per domain of application (mesh versus WSN). Indeed, separating my mesh and sensor activities is not judicious: some of them have common scientific bottlenecks. Sensor networks require however to *adapt* some algorithms and protocols, because they integrate an additional energy constraint, and because they use a low-cost and unreliable hardware. Sometimes it requires to re-design entirely the stack of protocols, while in other cases, the same algorithmic tools are used differently to solve these additional constraints.

In the chapter 2, I will expose my work on the topology control in the MAC layer: with which neighbor should I exchange packets to optimize globally the performance (energy, throughput, collisions)? By constructing a structure (e.g. a directed acyclic graph, a k-tree core), I propose to organize the network and use only one subpart of the radio links. This organization problem is transverse: which MAC structure is required to reduce the synchronization cost with preambles sampling protocols, or to reduce the energy consumption with IEEE 802.15.4? Which structure is required fro construct efficient routes in convergecast networks?

In the chapter 3, I will explain how multichannel may help so solve some of the problems described in the introduction. I will expose how multiplexing transmissions over different orthogonal channels (frequencies) for single or multi-radio nodes, with or without energy efficiency helps to reduce the number of collisions.

Finally, in the chapter 4, I will focus on the routing problem: how may I construct efficient routes over the MAC layers presented previously? I will present our interpretations about the experimental results obtained by sensorlab [Sen13], and its impact on the routing layer. I will explain in what the MAC and routing layers are closely inter-dependent, and the instabilities we have isolated in wireless sensor networks with RPL [Win+12].

I conclude this document by exposing a few trails I consider promising in the wireless multihop network research.

Chapter 2

Topology Control in the MAC Layer

During my PhD, I developed clustering and virtual structure algorithms to self-organize the network. Such a solution was, for me, an independent solution, and constitutes a separated layer, between the MAC and network layers.

I still consider that a network should not be considered *flatly*, without any hierarchy and any structure. This would create too much complexity to design efficient algorithms and protocols. OLSR has for instance chosen to rely on Multipoint Relay (MPR) nodes to reduce the control traffic [CJ03a]. In the same way, RPL uses a directed acyclic graph structure to route packets toward the border routes (sinks) [Win+12]. However, this organization should be considered in the protocol itself. In other words, mutualizing the organization among different layers presents an high abstraction cost in multihop wireless networks, while a *cross-layer* approach seems for me more accurate to solve this type of problem.

Thus, such self-organization is very close to the topology control problem: with which neighbor a node should choose to communicate? In particular, I should keep in the communication topology the good and stable radio links, which present an interesting energy efficiency, and which could constitute a *good route*[1]. In this chapter, I consider the self-organization structure as a **topology control solution** based on the construction of a connected structure (i.e. topology of really used links).

While the routing protocol establishes routes, and thus a hierarchy of nodes rooted at the destination, the MAC layer seldom relies on such organization. SMAC [Ye+04] proposes to create a scheduling of waking periods while maintaining the synchronization among neighbors to reduce the energy consumption of the MAC layer. However, all the links are assumed to be existent and used. On the contrary, IEEE 802.15.4-2006 proposes optionally to construct a tree rooted at the PAN coordinator (sink) in multihop networks.

We will see here how a self-organization may improve the MAC performance:

1. IEEE 802.15.4-2006 relies on a *cluster-tree* structure. While the standard specifies how a node associates with a neighbor, it does not specify which neighbors a node choose select. We will see that the association strategy has even a very large impact on the throughput and energy consumption;

2. synchronizing a pair of neighboring nodes allows the MAC layer to reduce the energy cost. For instance, SMAC [Ye+04] proposes to set-up a common sleeping schedule for all the nodes. In the same way, preambles techniques are less expensive if the pair receiver/ emitter knows their respective waking schedule. We will expose how a WCDS (Weakly Connected Dominating Set) structure may reduce the energy consumption by selecting the best radio links to use;

3. in mesh networks, we often assume that each router is equipped with IEEE 802.11 wireless cards. However, this protocol has been proved to perform very poorly in multihop topologies [Cha+05]. We will explain how we may modify IEEE 802.11 while using a *k-tree core* structure to reduce the number of collisions very significantly to increase the network capacity.

[1] I will expose later in this manuscript what I mean by a good route since this concept is quite multifaceted

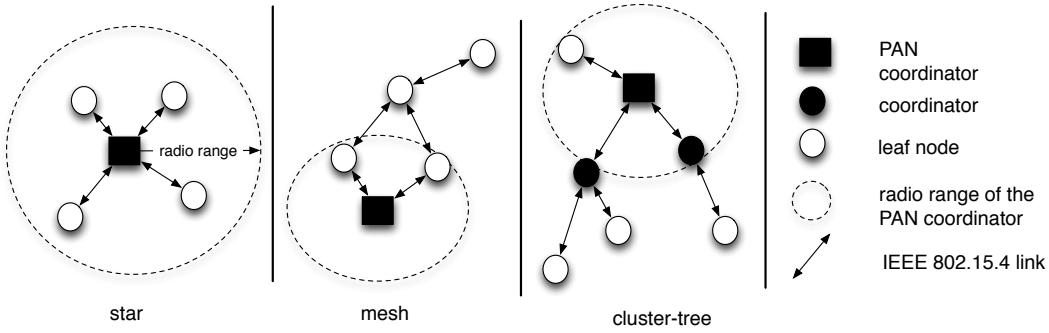


Figure 2.1: Possible topologies with IEEE 802.15.4-2006

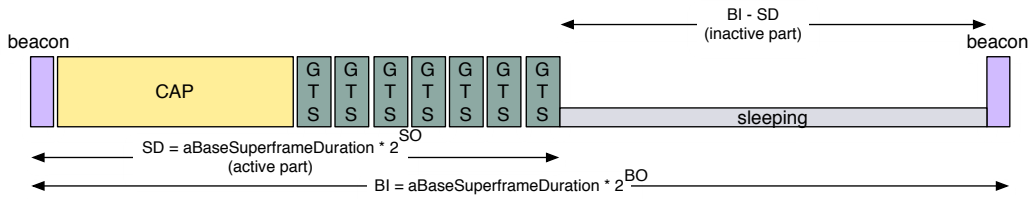


Figure 2.2: Superframe of IEEE 802.15.4-2006

2.1 IEEE 802.15.4 Fundamentals

IEEE 802.15.4-2006 is the MAC protocol proposed by the IEEE for low-power wireless actuator and sensor networks. A PAN coordinator serves as gateway between the devices and the Internet. Zigbee, implemented in many products, is an overset of the IEEE 802.15.4 features. It integrates all the medium access and the PHY layer, and adds new routing and addressing features (layer 3).

2.1.1 Topologies

The standard relies on three different (exclusive) topologies (Fig. 2.1):

star: the PAN coordinator communicates directly with the other nodes;

mesh: there does not exist any hierarchy: a node may send and receive a packet from any neighbor;

cluster-tree: the network topology is constructed iteratively, creating a tree rooted at the PAN coordinator. All the non-leaf nodes must relay the packets along the tree toward the PAN coordinator. These nodes are designated as **coordinators**.

Two categories of nodes exist:

the Reduced Function Devices (RFD): very energy constrained, these node wake up only occasionally to receive or send their packets. They must optimize their lifetime very carefully;

the Full Function Devices (FFD): these nodes are able to forward the packets of the other nodes. They participate consequently more actively in the network operation, authorizing for instance their neighbors to associate with the PAN coordinator by its intervention.

2.1.2 Medium Access

Besides, the protocol proposes two distinct operating mode for the medium access:

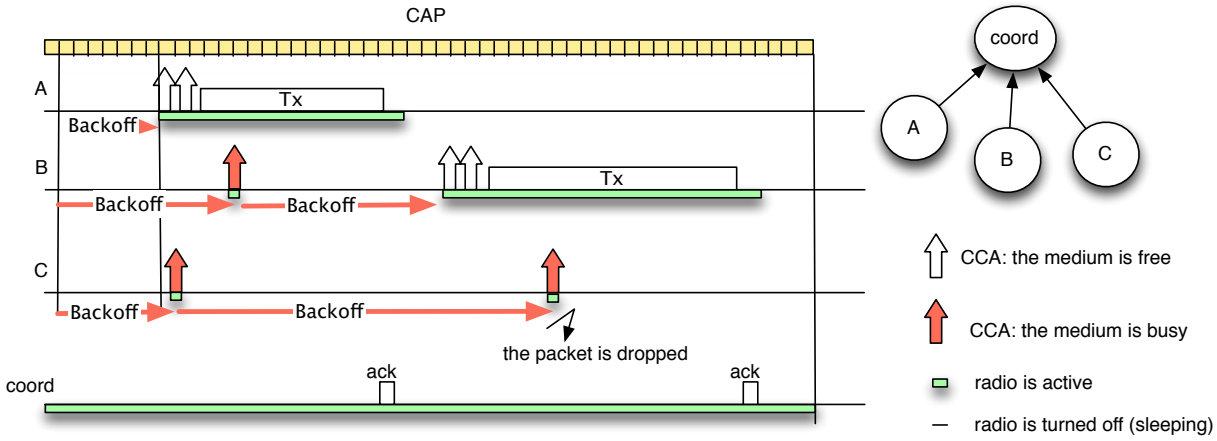


Figure 2.3: Medium Access with IEEE 802.15.4

non-beacon mode: two nodes may exchange directly packets at any time with a CSMA-CA variant;

beacon-enabled mode: time is divided into a superframe (Fig. 2.2). At the beginning of its active part, a coordinator sends a beacon. Then follows the Contention Active Period (CAP), during which each participant executes a slotted CSMA-CA to send its frames to the coordinator. Finally, the Guaranteed Timeslots (GTS), may be reserved by the nodes during the CAP. They are located after the reservation dedicated to the periodical transmissions of the reserving nodes.

The medium access follows the CSMA-CA approach:

1. the emitter chooses randomly a backoff value comprised between 0 and 2^{BE}. In beacon-mode, the emitter must wait the beginning of the next slot, else the countdown is immediately triggered.

2. the emitter must trigger two consecutive Clear Channel Assessments (CCA). If the medium is free, the node sends its frame, and waits for the acknowledgement if it is required;

3. if the medium is busy during one of the CCA, the emitter must increase its *backoff exponent* (BE) value and then trigger a new backoff;

4. if a frame has been transmitted too many times without being acknowledged (`macMaxFrameRetries`) or if the medium is busy too many times (`macMaxCSMABackoffs`), the frame is dropped.

A node may sleep during a backoff. Thus, the coordinator cannot send directly its frames to a child: it must wait an explicit request. This *indirect-mode* requires consequently a node to poll its coordinator periodically to ask for the buffered frames. Thus, a coordinator must piggyback in its `beacons` the list of pending destinations: children have to periodically listen to these `beacons`.

When a node is notified, it must send a `data-request` to the corresponding coordinator. This technique permits to optimize the energy consumption: the coordinator is the single node to stay awake during its active part. Other nodes have only to wake-up to receive or transmit their own frames, limiting over-listening.

This indirect mode is also particularly accurate for star topologies, with or without beacons. The PAN coordinator owns often unlimited resource and may listen continuously to request from its associated devices.

Figure 2.3 illustrates the star scenario in beacon-enabled mode. We can remark that only the coordinator is active during the whole CAP: other nodes stay awake only when they sense the channel (CCA), send a packet, or wait for a response. The node B has a packet to send: it triggers a first backoff, period at the end of which the channel is busy. The second backoff is chosen randomly after having incremented

the backoff exponent (BE) value. On the contrary, the node C has triggered two different backoff values, but senses a busy channel: it drops its frame.

This behavior is different from the IEEE 802.11 protocol, and leads to different performance. IEEE 802.15.4 has no residual backoff, and the nodes do not wait the end of a transmission to choose a new random backoff value. Since they don't stay awake during all the time, they have a different view as compared to IEEE 802.11. In IEEE 802.15.4, a strict focus has been given to energy savings (turning off the radio) compared to the throughput (minimizing the delay between two frames).

2.1.3 Superframe Organization

The superframe duration is defined by the parameter Superframe Order (SO) while the interval between two `beacons` is defined by the Beacon Order (BO) (Fig. 2.2). In conclusion, the duty cycle ratio is defined by 2^{SO-BO} [NAT12].

The superframes must be appropriately scheduled to minimize the number of collisions while maximizing the sleeping time. The standard mentions that the active parts of a coordinator and one of its children must be interspaced by $StartTime$ [802c, p 169].

2.1.4 Energy Savings

IEEE 802.15.4-2006 targets mainly the low-power single hop networks. The star topology is particularly well considered: only the PAN coordinator has to stay awake continuously. Other nodes just have to wake-up to transmit their `data` frames or a `data-request`.

The problem is a little bit more complicated in multihop topologies. We make a clear distinction between the following cases:

mesh: only the beaconless mode is possible since a node may exchange packets with any neighbor. Thus, a node has to stay awake continuously to receive a frame at any time from any neighbor. Energy saving is only possible for the Reduced Function Device (RFD) since they don't wait for any packet.

cluster-tree without beacon: a coordinator must also stay awake in this scenario to receive packets from its children. No energy saving is possible for Full Function Devices (FFD);

cluster-tree with beacon: a coordinator must stay awake during the whole active part of its superframe, and to send packets to its parent in its active part. During the rest of the time, it may turn off its radio.

Finally, only the cluster-tree topology in beacon-enabled mode authorizes to save energy in multihop topologies.

2.2 IEEE 802.15.4: with which parent should a node be associated to save energy?

IEEE 802.15.4 proposes an association mechanism to construct iteratively the cluster-tree structure. A coordinator already associated accepts the associations coming from its neighbors.

In beacon-less mode, the nodes must implement an active discovery mechanism (active scan): they send `beacon-request` to their neighbors. On the contrary, in beacon-enabled mode, a node may passively until it receives a `beacon`: the frame contains all the information required for the association. Then, the node sends an `association-request` to the coordinator. Follows an exchange of control frames to finalize the association and to allocate one short address (16 bits).

While the standard describes *how to associate with*, it does not describe *to which a node should associate with*. Strangely, only a few papers studied the impact of the parent choice on the performance. Cuomo et al. [Cuo+08] have studied the cluster-tree characteristics when a node associates with the first listened coordinator with a minimum radio link quality. The authors measure in particular the number of children and the depth, two important parameters for Zigbee. Cuomo et al. [Cuo+09] have also analyzed

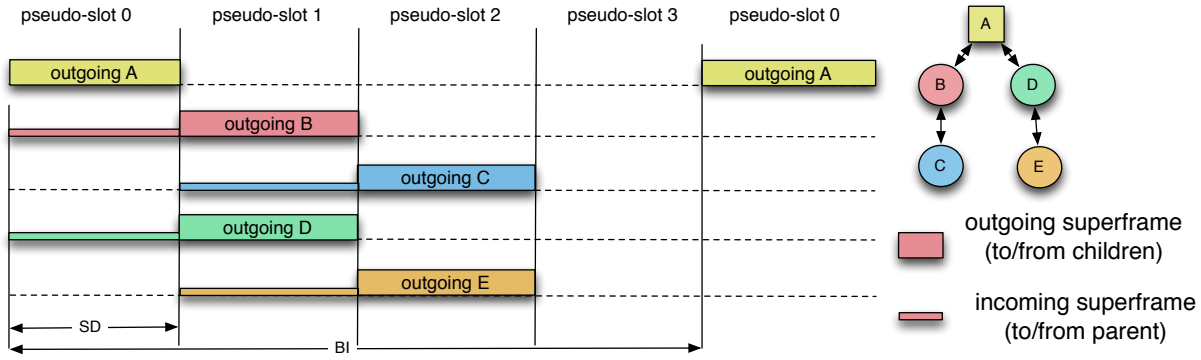


Figure 2.4: Scheduling the active parts with 4 pseudo-slots (BO-SO=2)

the impact of mobility on the cluster-tree structure. Cuomo et al. [Cuo+13] have studied the impact of the PAN coordinator location. They propose to locate the gateway in the nodes which present the largest *centrality* property. Claudios et al. [Cla+07] proposed to re-organize the cluster-tree when new nodes are inserted in the network, to minimize the end-to-end path length.

Scientific challenge

What is the impact of the topology construction algorithm of the IEEE 80215.4 cluster-tree on the throughput and the energy consumption? [TD11]

Indeed, it is important to note that throughput and energy consumption are intimately related in WSN: if the protocol achieves a larger throughput with the same parameters, this means the duty cycle ratio may be reduced. This mechanically decreases also the energy consumption.

This work has in particular been done jointly with **Benoit Darties** (after his post-doc in the LIG).

2.2.1 Assumptions

We consider a network with a convergecast traffic pattern, where all the packets are transmitted to the PAN coordinator. We assume the `beacon` losses can be neglected, and collisions arise mainly among data packets. A technique such as proposed by Koubâa et al. [Kou+08] may be implemented to schedule the beacons accurately.

We assume that the active parts of one node and those of its parent are directly consecutive. Thus, the `StartTime` value in the standard is considered constant. We assume that all the nodes use the same SO and BO value, as the standard advocates. And we neglect also clock drifts. Time may be divided into *pseudo-slots* (of duration SD), as depicted in Figure 2.4: one pseudo-slot comprises exactly one outgoing / incoming superframe (one active part). Since we consider a constant `StartTime`, the depth of a node deterministically gives the pseudo-slot used by its active part. We remark that we have exactly $n_{slot} = 2^{BO-SO}$ timeslots. In figure 2.4, B and D are children of the node A and use consequently the pseudo-slot 1.

We differentiate the power levels required by a node to transmit (P_t), to receive (P_r) or to listen (P_i). We neglect the energy in sleeping mode.

We model the network by a communication graph $G = (V, E)$, where V is the collection of vertices and E the collection of edges. A conflict graph G_c may be associated with G: each vertex of G_c represents a radio link and they are neighbors in G_c iif they interfere with each other.

2.2.2 Model

We now describe how we may translate the cluster-tree construction and the MAC behavior into MILP constraints. The objective will provide the criteria to maximize (here the throughput) in our optimization problem. A formal description is provided in [TD11].

Tree structure: A node must be associated with one unique parent[2]. Besides, only the link between one node and its parent is *active*.

Energy: we neglect the energy consumed when a node has turned off its ratio (inactive parts of the superframes). A coordinator rest awake during its active part. Besides, any node receives a beacon if it is not the PAN coordinator and transmit its traffic to its parent. The traffic is translated into a ratio of time, permitting to translate it directly into energy. Besides, we assume a leaf does not maintain one active part: it does so only when a child is associated (cf. section 3.4.1).

We neglect here the fact that a node may turn-off its radio in backoff mode or when it does not have any frame to transmit during the active part of its parent. We might take into account this feature by computing the average time required for a node to transmit its traffic. However, the backoff time is practically correlated with the number of interfering nodes (siblings) and their traffic. Such duration can only be coarsely approximated with a MILP formulation.

Flow conservation: we have classical flow conservation constraints: all what enters a node and what is generated by the node equals the traffic transmitted to its parent. Besides, the PAN coordinator *consumes* all the packets generated by all the nodes.

Scheduling active parts A coordinator has only one active part. We translate into linear inequalities the fact that two active parts of the cluster-tree hierarchy are consecutive. Some specific inequalities handle the case where the parent uses the last pseudo-slot : we have a kind of modulo.

Bandwidth sharing: The bandwidth wasted by collisions must also be considered. Indeed, CSMA-CA does only limit the number of collisions.

In particular, Pollin et al. [Pol+08] highlighted the fact that the bandwidth wasted by collisions is directly linked with the number of interfering stations. To approximate the number of collisions, we interpolated the results obtained in [Pol+08, section V, fig. 9]. We model the quantity of bandwidth dedicated to collisions as proportional to the number of contending nodes.

We must consequently for each clique in the contention graph estimate the radio bandwidth wasted by collisions, proportional to the number of interfering nodes which are awake during a given timeslot.

Objective: We choose to maximize the throughput (and thus the associated energy consumption).

2.2.3 Numerical Results

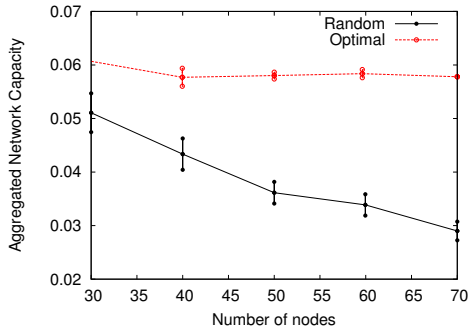
We generated random topologies with an unit disk graph model (i.e. a link exists between two nodes iif their geographic distance is less than a threshold value). The nodes are distributed in a disk, with one centered PAN coordinator. We could have used any more complicated model, weighted for instance by the packet delivery ratio of each link. However, we should in this case have considered the radio link quality in the cluster-tree selection. This topology feeds Cplex 12.0 so that it solves the optimization problem. We have represented 95% confidence intervals, and have considered 4 pseudo-slots.

We compared two strategies to select the parent:

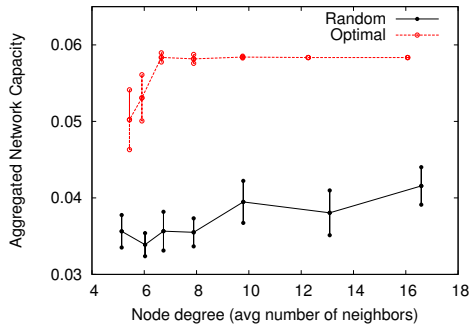
random: a node associates with the first neighboring coordinator;

optimal: the pseudo-slot assignment is given directly by the MILP.

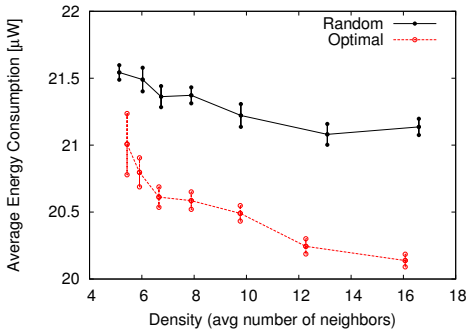
[2]The reader can remark than by removing this constraint, we authorize the creation of a DAG structure, rooted at the PAN coordinator. The MILP formulation keeps on holding.



(a) Capacity vs. nb. of nodes (average degree = 8)



(b) Capacity vs. avg. degree (50 nodes)



(c) Energy consumption versus avg. degree (50 nodes)

Figure 2.5: Performance of different algorithms to construct a cluster-tree

We can remark that the random strategy is clearly suboptimal compared to the optimal one, concerning the network capacity (Fig. 2.5a). This remarks holds whatever the density is (Fig. 2.5b). Denser is the network, larger is the choice among the different possible parents: a node has a larger gain when choosing the best one. Dividing by 2 the duty cycle ratio leads in particular to the same throughput: energy is consequently really saved. Figure 2.5c strengthens this conclusion: even with a constant duty cycle ratio, the optimal strategy leads to less collisions, and consumes less energy.

Conclusion: the association to the first parent is simple but clearly does not lead to good performance.

2.2.4 Limits and Perspectives

This formulation is sufficiently flexible to be extend to other scenarios:

bidirectional traffic: if the traffic is bidirectional, we may set a ratio between the upload and the download directions. If radio links are bidirectional, the equations keep on holding, the traffic being just separated in te upload and download direction;

multiple active parts: to increase the network capacity, some nodes may have a longer listening time, particularly for nodes close to the sink which have a larger traffic to forward. It should be sufficient to maintain them active during several active parts;

DAG: one unique constraint needs to be removed to consider a directed acyclic graph and not anymore a tree;

radio link quality: practically a radio link presents a given quality (e.g. delivery rate). We may modify our model to integrate this constraint, by using a weighted graph (the weight of an edge would be

the delivery rate of the associate radio link). The traffic generated on the edge (u, v) would be multiplied by the inverse of the packet delivery ratio to take into account retransmissions;

scheduling: if we remove the precedence constraints between the pseudo-slots of one node and its parent, we would obtain an implicit scheduling, computed by Cplex. However, the resolution complexity explodes very quickly: the optimal solution is complicated to be obtained.

Obviously, our approach, like any other model, presents some limits. In particular, the complexity increases very quickly when we consider more pseudo-slots. Only the small topologies may be solved in a reasonable time (a few hours). Optimization specialists would surely accelerate the resolution by using the column generation technique for instance [Des+05]. However, we focused here more on the comparison of different heuristics in terms of bandwidth. Our objective consisted in proving a gap still exists between the simple association strategy and the optimal one.

We also assumed here that the bandwidth wasted by collisions is proportional to the number of contending nodes. However, we assume that all the emitters have the same quantity of traffic to send, whatever the size of their subtree is. Taking into account the multihop topology accurately would be surely more complicated. However, we will see in chapter 3.4.2 how we may reduce the number of collisions in IEEE 802.15.4.

2.3 How can we reduce the synchronization cost by using a structure of weakly connected dominating set?

Many papers focused in WSN on the energy consumption. Since most of the energy is spent by the radio module even when the node is in idle-listening, we must turn off the radio as much as possible [Fee99]. However, this technique implies a deafness problem: the emitter must know a priori when the receiver is awake to send a frame.

A widely used technique in the MAC layer consists in transmitting a preamble:

- either the emitter does not know when the receiver wakes up. In this case, the emitter sends a preamble during a time at least equal to the waking cycle of the receiver. When a preamble is detected by the receiver, it stays awake to receive the data frame which follows the preamble. Preamble sampling techniques permit to reduce the preamble length when the receiver awakes during the preamble.
- or the emitter knows the waking time of the receiver. It will send a shorter preamble, just to take into account the maximum clock drift of the receiver. When synchronization packets are interspaced, the preamble is consequently longer.

In the asynchronous case, preambles are long and transmitting a data frame is expensive. On the contrary, in the synchronous scenario, the preamble is shorter, but most of the energy may be consumed by the synchronization.

Scientific challenge

We propose here to study the tradeoff between both approaches: which pairs of nodes should be synchronized to make the network energy efficient [The+10] ? Besides, how may we implement an efficient broadcast with this type of protocols [Bac+10] ?

This is a joint work with in particular **Abdelmalik Bachir** (post-doctoral fellow at Imperial College) and **Nesrine Chackchouk** (master student in the LIG).

2.3.1 Related work

WiseMAC [EH+03] is one of the first protocols using synchronous preambles. Each node maintains its own sleep-wake cycle, piggybacked in its acknowledgement (i.e. next waking time). Thus, each node has its own waking time, increasing the network capacity. However, broadcast is expensive: all the neighbors are not awake simultaneously, requiring to duplicate the packets.

Scheduled Channel Polling (SCP) [YH06] argued the transmission of synchronization may counterbalance the interest of short preambles. Thus, SCP proposes to maintain the same wake-sleep cycle for all the nodes: all the nodes synchronously wake up to send and receive frame. In particular, deafness is impossible. However, the network capacity is greatly reduced (in the same order as the duty cycle ratio). This problem is ever amplified by the collisions created by a burst of transmissions by all the emitters which have meanwhile buffered their packets.

Crankshaft combines both TDMA and preambles: each receiver owns a slot, and the emitters use a preamble to solve the contention among different transmitters to the same node [HL07]. Timeslots are different for unicast and for broadcast to avoid duplicating the packets. Y-MAC [Kim+08] adopts a similar approach while increasing the number of slots when the traffic pressure increases. Wavenis [Wav] adopts a similar technique, combining frequency hopping to increase the robustness to narrow band interference.

Crankshaft, Y-MAC, and Wavenis increase the capacity but also the control traffic, because of a dedicated broadcast channel. Thus, selecting the optimal number of slots for unicast and broadcast in the whole network is complicated to achieve practically.

The approach we present here is inspired from SPAN [Che+02], creating a backbone of nodes forwarding most of the traffic. However, we don't use any geographic location to route packets. We only focus on the energy drained by synchronization.

2.3.2 Synchronization through a weakly connected dominating set

Synchronization cost

Let focus here on the energy to maintain the network (i.e. separating the energy consumed for data frames). With preamble sampling, the energy cost consists in sampling the channel, and in sending and receiving the synchronization frames. If we consider periodical traffic, both data and synchronization frames are periodical. We quantified the energy consumed for synchronization and for preamble samplings. We can consequently compare accurately the different techniques.

Interest of a WCDS for the synchronization

We aim at limiting the number of reference nodes while maintaining the connectivity. This problem is directly related to the construction of a Weakly Connected Dominating Set (WCDS). Let consider a graph $G(V, E)$ where V is the set of vertices and $E \subseteq V^2$ the set of edges. An edge (u, v) exists in the graph iif both nodes can communicate with each other.

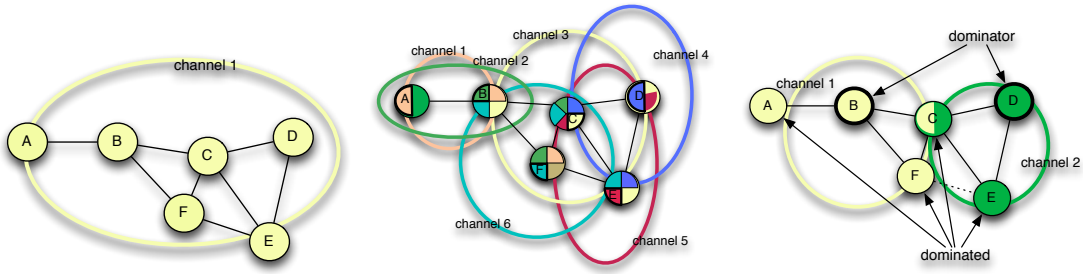
Formally, a WCDS satisfies the following constraints:

$$\forall d \notin \text{WCDS},\ \exists d' \in \text{WCDS} | d' \in N(d) \tag{2.1}$$

$$G(V, E') \text{ connected} | E \supseteq E' = \{(u, v)\}, u \in \text{WCDS}, v \in V \tag{2.2}$$

The nodes which own to the WCDS are denoted *dominator* and the other nodes are *dominated*.

For the synchronization point of view, the dominators may serve as reference nodes and the dominated nodes may be their *followers*, saving the clock offset of their dominating neighbors. Thus, all the links (dominator, dominated) are synchronized and may use short preambles. Other links must on the contrary use long preambles. A WCDS guarantees, by construction, that a path exists between any pair of nodes, and this path uses only *synchronized* links. If we minimize the number of reference nodes, we reduce the energy consumption to maintain the synchronization while maintaining a connected network.



(a) SCP (b) Crankshaft (c) WCDS

Figure 2.6: Synchronization maintenance

Illustration

Let consider the cost of synchronous preamble sampling with different access methods. We propose to consider the topology illustrated in figure 2.6 and we focus on the energy consumed by the node C. We only consider the maintenance cost (we discard the energy to receive and transmit data packets).

SCP sends a SYNC to propagate its wake-sleep schedule. Consequently, a node receives as many SYNC as it has neighbors. Moreover, it must sample the channel to receive packets. Finally, C has an average power of $\mathcal{P}_{\text{ref}} + \mathcal{P}_{\text{samp}} + 4\mathcal{P}_{\text{foll}}$.

With Crankshaft, each node consumes the same energy as with SCP to maintain the synchronization and reeve packets. Besides, the broadcast channel must also be sampled periodically. C consumes consequently $\mathcal{P}_{\text{ref}} + 2\mathcal{P}_{\text{samp}} + 4\mathcal{P}_{\text{foll}}$.

In the WCDS structure, B and D are dominators and serve as reference nodes. C acts as a gateway and has to listen both neighbors. However, it does not transmit any synchronization packet. Its average power is $2 * (\mathcal{P}_{\text{foll}} + \mathcal{P}_{\text{samp}})$. The cost is finally reduced.

WCDS structure

We propose a simple algorithm to construct the WCDS, based on a tree rooted in the sink. Each node maintains the identifier of its parent in the tree, and we guarantee a strict alternation of the states (dominator / dominated) along the tree. To minimize the number of reference nodes, we use a random timeout, to force a node to associate with any neighboring dominator.

We propose here two variants:

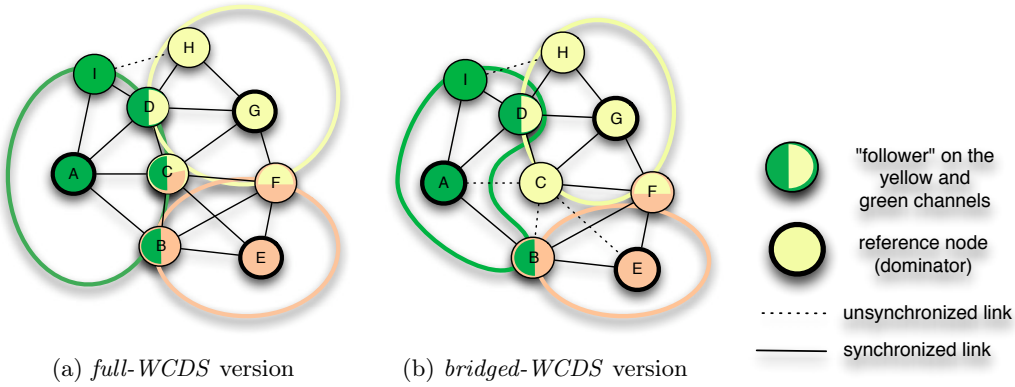
full-WCDS: a *follower* is synchronized with **all** the neighboring reference nodes (Fig 2.7a).

bridged-WCDS: bridges are elected by each reference node to rely other reference nodes with a strictly smaller id (Fig 2.7b). These reference nodes are at most 2 hops far: the quantify of information to store in the neighboring table is consequently limited..

Performance evaluation

We considered only the energy consumed by the radio module. We use the standard values of a wavenis chipset [Wav]: bandwidth=19.6kbps, θ=$20 \cdot 10^{-6}$, T_{CI}=1s, T_{SI}=20min, T_{SYNC}=0.012s, T_{preamble}=0.096s, P_{tx}=45mWatt, P_{rx}=17mWatt, and $\mathcal{P}_{\text{samp}}$=32.51$\mu$Watt. We generate one packet every 2 seconds (10,000 packets) coming from a random source to the sink. We measure the energy of over-listening, reception, transmission, and channel sampling. With a proprietary graph simulator, we estimate the energy consumed by such network [Gra].

Because of concision, we only represent here the average total energy (Fig 2.8). A large density impacts significantly the performance of SCP and Crankshaft: a node has to listen to a larger number of neighbors. On the contrary, the WCDS solution selects the radio links to maintain synchronized, and we reduce both the number of synchronization packets and the overhearing. Obviously, the bridged-WCDS



(a) *full-WCDS* version (b) *bridged-WCDS* version

Figure 2.7: Example of a WCDS in *full* versus *bridged* mode

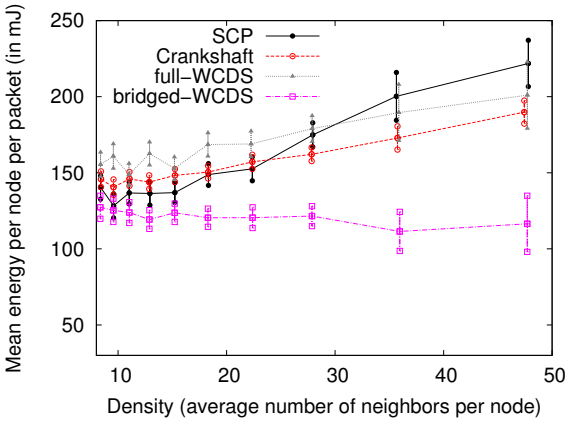


Figure 2.8: Total energy per node drained in forwarding one packet in function of network density (node degree).

version, while being more complicate to maintain, consumes a smaller quantity of energy. In conclusion, a topology control is efficient to reduce the synchronization cost: using a smaller number of radio links permits to exploit more efficiently the network.

2.3.3 Broadcast in a multichannel MAC

While maintaining the network synchronized may be expensive, a broadcast transmission may also have a large impact on the energy consumption. We use here the concept of multichannel in its larger signification: timeslot, frequency, etc. By multichannel, we denote the impermeability of the different channels: a receiver is deaf for the channels it does not listen to.

In this multichannel environment, broadcast may be expensive: a transmitter may have to duplicate the packet to *cover* each of its neighbors. Another solution based on a channel dedicated to broadcast may improve the energy efficiency. We make a distinction between the following types of broadcast:

1. broadcast to neighbors (layer 2): a packet has to be received by each node present in the neighborhood table;

2. discovery broadcast (layer 2): a packet must be receive by any node in the radio range. This node may be still unknown;

3. flooding (layer 3): a packet must be received by each network participant.

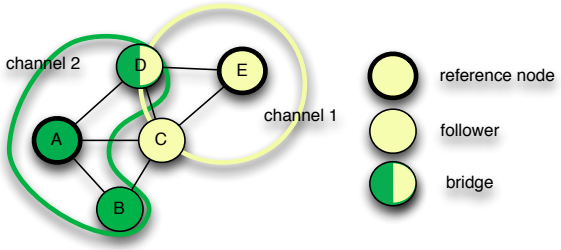


Figure 2.9: One virtual broadcast channel per cluster (=reference)

Consequently, a flooding may rely on a collection of neighbor broadcasts (layer 2).

Scientific challenge

How should we structure / organize the transmissions and the sleeping time while taking into account the broadcast to neighbors?

We proposed to use the WCDS structure presented previously for synchronization. Since some of the nodes are reference nodes for the synchronization process, we re-use the same clusters for broadcast [Bac+10].

Based on this organization, we propose two different methods:

1. a common channel for discovery (*à la* SCP). Each node must listent to this channel to discover a new neighbor. It is sampled every T_{SI}. We modify the previous proposition by forcing the bridges to relay synchronization frames from their reference nodes. We have consequently a global synchronization, and not anymore restricted to a cluster C. This global synchronization helps to reduce the discovery time by setting up a common discovery channel.

2. Each dominator maintains a broadcast channel with all its followers (Figure 2.9). Consequently, a bridge node has to listen to as many channels as clusters it owns to.

For a flooding, we may use the broadcast cluster channel, and the WCDS structure: a bridge relays the packet to its neighboring reference nodes. One follower just listens to the flooding packets and does not forward them.

We re-use here the same parameters as previously (cf. on page 14). Figure 2.10 illustrates the energy consumption of the most loaded node. We have measured the performance of SCP (Single Virtual Channel = SVC), Crankshaft (Multiple Virtual Channel = MVC) and CVC (Clustered Virtual Channel). We have also introduce a new protocole Optimized Virtual Channel (OMVC) corresponding to a new version of crankshaft using an optimal frequency sampling rate for the broadcast channel. We can remark that our proposition efficiently reduces the energy consumption for a flooding. Besides, all the propositions are scalable: their performance is stable even when the number of nodes increase. Indeed, a source is chosen randomly: the number of floodings is constant and the protocols succeed to reduce the number of local broadcast required to forward the packets.

2.3.4 Limits and Perspectives

We have seen here that a structure using a Weakly Connected Dominating Set (WCDS) helps to reduce the energy consumption for both synchronization and broadcast. While the MAC broadcast is vastly used by most network layers (to announce routes, metrics, addresses), this problem is strangely seldom

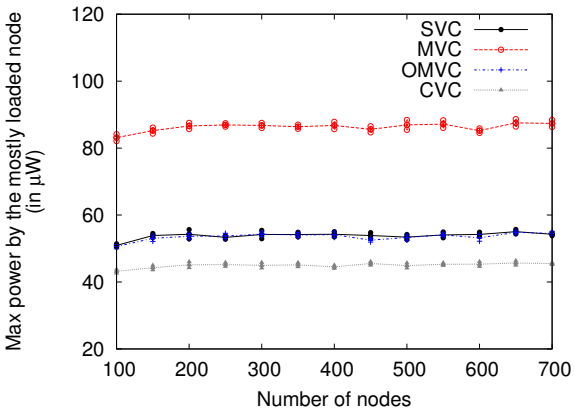


Figure 2.10: Average power of the most loaded node

studied. This study is a first step toward a better understanding of the tradeoff between unicast and broadcast optimization for energy consumption.

This study is strongly dependent on the MAC technique (with preambles). However, we may extend this WCDS structure to other protocols. For instance, IEEE 802.15.4-2006 in beacon-enabled mode uses a tree structure. A WCDS may be preferred so that each dominator is a IEEE 802.15.4 coordinator, and its children its followers. Thus, we find the same type of concepts in other scenarios.

The algorithm to construct the WCDS is very simple: the focus was rather given to the interest of a WCDS in the MAC layer. We must consequently now propose a self-stabilized and robust WCDS algorithm. We conjecture a greedy algorithm is probably not the optimal solution.

We focused mostly on the average energy consumption. However, the network lifetime is strongly correlated with the maximum energy (i.e. the bottleneck). We still have to propose strategies to distribute the roles to the nodes. This problem, related to the WCDS construction and maintenance, seems complex: we must maintain the global connectivity, minimize the dynamic while distributing fairly the load.

Finally, we neglected here the variable radio link quality. A bad radio link may be selected to be part of the WCDS: the network would perform badly by increasing the number of retransmissions and packet losses. A black list mechanism such as [Fab+12] may be conceivable, or the construction of a WCDS based on a radio link / path quality metric, such as the DODAG of RPL [Win+12].

2.4 What structure may be efficient to organize the transmission in a convergecast network?

We propose here to forget the energy efficiency of wireless sensor networks and to focus rather on the network capacity problem. By capacity, we designate the maximum achievable throughput:

- either we consider the aggregated throughput (sum of the throughput of each flow);
- or we take into account fairness constraints and measure the throughput achieved by the weakest flow (max-min fairness).

The first case does not take into account the specific nature of multihop radio networks: we focus here on the second objective.

IEEE 802.11 [802a] represents the widely used MAC layer in hotspot networks. The CSMA-CA protocol is very flexible to handle the traffic efficiently in this scenario. However, it performs very poorly in multihop topologies [Cha+05], with in particular unfairness problems. In the 3 pairs topology, the pair in the middle interfere with the other two. The independent pairs consume all the bandwidth: the pair in the middle may transmit one packet only when the two other ones are silent.

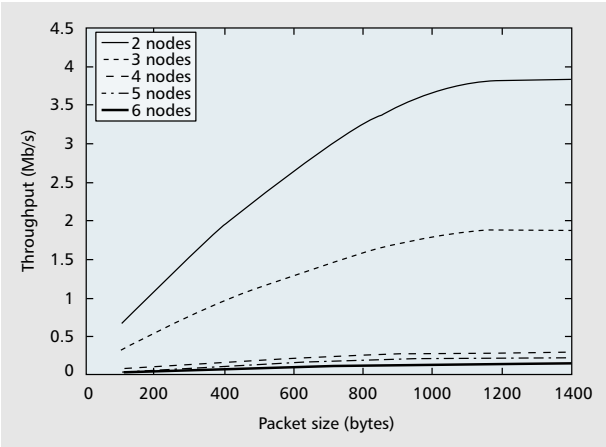


Figure 2.11: Achievable throughput in a chain [Cha+05]

If we consider a multihop flow, collisions arise very quickly and impact negatively the throughput. Figure 2.11 extracted from [Cha+05], represents the throughput of a chain with a variable length. If a packet is relayed over 4 hops, the throughput is almost null.

If we focus on the convergecast trafic pattern (every packet is transmitted to the sink), how should we organize the transmissions efficiently to remove the IEEE 802.11 problems? We aim here at studying jointly the bandwidth allocation (MAC layer) and the paths (routing) since both problems are intimately related. Besides, creating a (MAC and routing) structure permits to organize the transmissions and to reduce the number of collisions. We propose here to use a k-tree core structure (tree with K leaves, rooted in the sink), particularly efficient in such scenario.

Scientific challenge

When the network presents a convergecast traffic pattern, how should a node relay efficiently its packets toward the sink considering jointly the MAC and routing layers [The11] ?

2.4.1 Related work

In wireless mesh networks, some researchers have proposed to assign the channels efficiently to the different nodes and interfaces in order to multiplex efficiently the transmissions [KV06; Ram+06; RC05; NN09]. In most cases, the bottleneck resides around the sink, most sensitive node in the network [Kar+08]. Raniwala and Chiueh [RC05] have focused on finding a routing metric to construct a routing tree rooted in the gateway. Then, they assigned a channel to each radio link, based on their load. Ramachandran et al. [Ram+06] have proposed to assign channels starting from the most constrained links (around the gateway). Nguyen and Nguyen [NN09] extended this solution to multicast. However, all these approaches require multi radio nodes, and color the links in a centralized manner

Kyasanur and Vaidya [KV06] introduced dynamic interfaces, switching dynamically their channel. However, the authors still assume that each node has a static interface to avoid the deafness problem (i.e. the emitter does not the channel used by the receiver).

In Wireless Sensor Networks, most of the protocols focus on the energy consumption rather than the capacity. Kulkarni et al. [Kul+06] proposed for instance to jointly optimize the MAC and routing layers

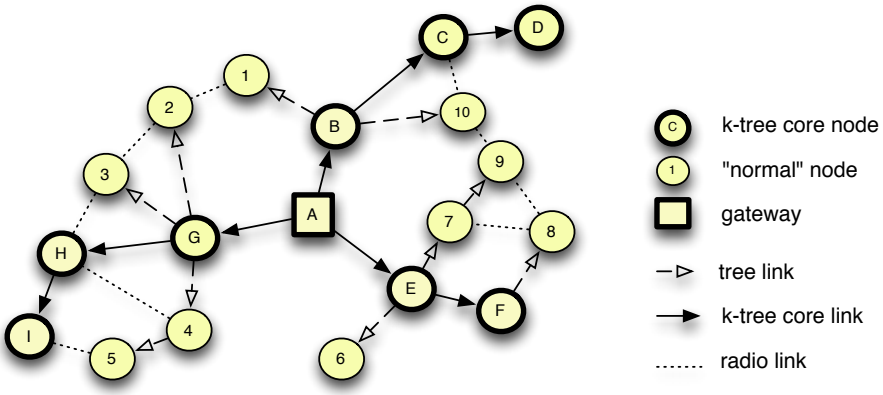


Figure 2.12: Tree structure for C-MAC (here a 3-tree core)

to maximize the number of sleeping nodes. However, the authors focus on the low traffic scenarios. We rather chose to maximize the network throughput.

To defeat the funneling effect [Ahn+06], it may be accurate to construct a TDMA scheduling in the MAC layer such as [Rhe+08]. Macedo et al. [Mac+09] proposed to extend this solution by measuring the interference level. Zhang et al. [Zha+08] optimized the number of retransmissions toward the sink. Chen et al. [Che+11] rather consider this problem has to be solved in the routing layer: we consider on the contrary the most important effects (collisions) occur in the MAC layer.

We adopt an approach similar to [Ahn+06] mixing CSMA without contention, depending on the constraints of the emitters. To avoid using a TDMA scheduling (requiring a global synchronization and computation), we rather adopted an approach based on dynamic reservations, closer to [Lu+04] proposing a *more to send* frame to maintain the nodes awake along a path.

C-MAC uses a k-tree core first introduced by Peng et al. [Pen+93]. A k-tree core is a tree with k leaves which minimizes the average distance from any node to the k-tree core. Srivastava and Ghosh [SG02] and Srivastava and Ghosh [SG03] extended this algorithm to provide a distributed version, used for routing. Li et al. [Li+08] used it for multicast. A k-tree core is particularly well suited for our problem: if the medium access is more efficient for k-tree core nodes, we minimize the average distance (i.e. number of transmissions) to reach these efficient nodes.

2.4.2 A structure to organize the transmissions: joint-optimization MAC / routing

We are convinced we must jointly optimize the MAC and routing layers. Since the gateway constitutes the bottleneck, we should organize efficiently the transmissions around the sink. Since only the largest group of interfering links counts [Kar+08], C-MAC proposes to regulate the transmissions only around the sink.

We propose to create a kind of *highways* :

- highways are paths constituted by nodes with a privileged medium access, with a minimal number of collisions. It is easier to solve the contention problem among a small number of contenders;
- other nodes just relay their packets to the closest highway node, in a best effort way.

We propose to adopt a k-tree core structure as illustrated in figure 2.12. A k-tree core is a tree with k leaves (here 3). Nodes in bold represent the 3-tree core and will have a privileged medium access.

C-MAC uses a reservation oriented mechanism: a node becomes *privileged* during a short time. To distribute this privilege, we use the tree structure: a token is generated by the sink, and propagated along each of its branches. When a node receives the token, it becomes privileged during a finite time. If

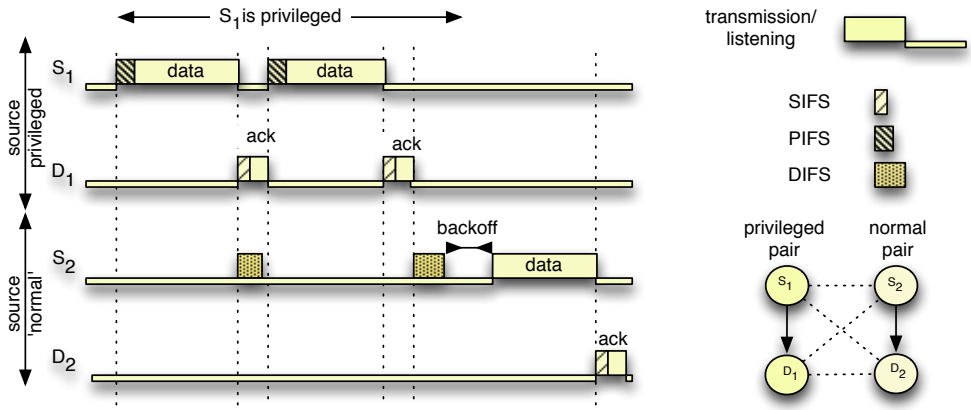


Figure 2.13: Medium access for privileged nodes

tokens are sufficiently interspaced, two privileged nodes cannot interfere: the token of the other branch is sufficiently far.

The number of branches should be chosen carefully:

- too many branches increases the delay before a node receives again the token. The bandwidth per branch is reduced, and the bandwidth wasted by guarding time increases mechanically;
- with too few branches, a node has to relay its packets farther to reach an highway node. This would increase the number of collisions.

2.4.3 Medium Access

Let now focus on the detailed MAC mechanisms of C-MAC. Figure 2.13 illustrates the difference between one *privileged* node (part of the k-tree core and which has received a token) and one normal node (does not own to the k-tree core). The privileged node should have access to the medium without contention: we propose to use the PIFS duration (similarly to an access point in PCF mode). In this way, we minimize the modifications of the IEEE 802.11 standard to support C-MAC.

On the contrary, normal nodes use the normal inter frame space of IEEE 802.11: the privileged node will **always** win. In other words, the normal nodes place their transmissions in the silence of their neighboring k-tree core nodes. This scheme is efficient only if the traffic of these normal nodes may be neglected compared to the traffic forwarded by the k-tree core.

If we don't have any hidden terminal, the privileged pair will receive the whole bandwidth. We can remark that only the k-tree core nodes must execute a slightly modified version of IEEE 802.11.

Figure 2.14 illustrates the propagation of a token along the k-tree core. The gateway generates a token and chooses a neighbor part of the k-tree core. It sends a `Clear-To-Receive` (CTR) to this neighbors, notifying it may now transmit the packets it has buffered. After having received the `CTR`, this node becomes *privileged* and monopolizes the medium during `privileged-duration`. After this duration, it just has to relay the CTR to its own child in the k-tree core.

The gateway interspaces sufficiently its CTR by $CTR_{hops} * privileged_duration$. CTR_{hops} represents the average number of hops after which we may neglect interference among branches (practically $CTR_{hops} = 2$ or 3). We can remark that the k-tree core should be as *straight* as possible: branches should be spatially balanced, and one branch should grow in a straight line.

To limit the impact of hidden terminals, the `CTR` act as a `CTS`: any node receiving a `CTR` must update its NAV to block any transmission during `privileged-duration`.

We optimize the routing scheme for this MAC: each *normal* node must forward its packets to the closest k-tree core node. Intuitively, we follow an *hot-potato* approach: a packet is forwarded to the most efficient nodes.

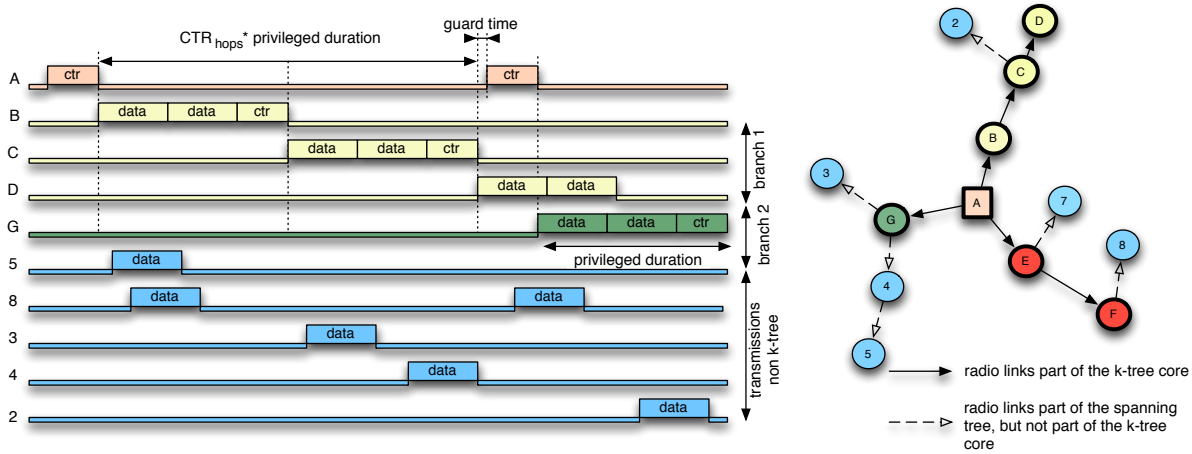


Figure 2.14: Forwarding a CTR and data transmission in upload (nodes → root) with $CTR_{hops} = 2$

2.4.4 Construction of a k-tree core

A k-tree core extracts the k leaves that minimize the average distance from any node to the k-tree core [Pen+93].

Formally, we note $l(T)$ the number of leaves in the tree T and $d(A, B)$ the distance in hops between the nodes A and B. In the same way, the distance of a node N to a set of nodes $\mathcal{S}$ is the distance of N to the closest node which owns to $\mathcal{S}$:

$$d(N, \mathcal{S}) = min_{M \in \mathcal{S}} \left(d(N, M) \right) \tag{2.3}$$

If KT is the k-tree core of T, we have the following property:

$$KT \subset T \tag{2.4}$$

$$l(KT) = k \tag{2.5}$$

$$Objective: \ min \sum_{N \in T} d(N, KT) \tag{2.6}$$

Obviously, the k-tree core we construct should be rooted in the gateway. We don't have to change the root, compared to the other algorithms in the literature.

Our approach is derived from the algorithm proposed by Peng et al. [Pen+93]. We re-use in particular the compact form they used to report the gain (*savings*) of the node choice to be part of the k-tree core. Intuitively, a node collects the gain of all its children, corresponding to each of their subtree. It then updates its gain if itself and its best child are chosen to be part of the k-tree core. A node then reports in its `hellos` packets its gain and thus of its $k - 1$ largest gains from its children. By aggregating this information along the tree, the root is finally able to select the best k children with the largest gains. Possibly, a child may be chosen for several branches, but this is very unfrequent in practice.

In such algorithm, we assume we use a tree of shortest routes, formerly constructed with the `hellos` packets.

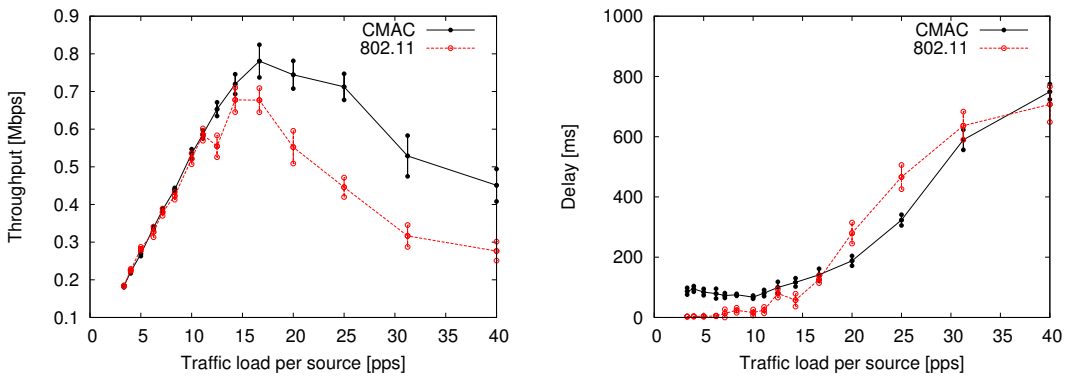
2.4.5 Performance evaluation

We simulated C-MAC with opnet and the default parameters as represented in table 2.1. We compared the performance of C-MAC with IEEE 802.11 DCF, protocol modified by C-MAC, and representative of the CSMA-CA family. More results are discussed in [The11]. Each node generates one flow toward the sink (to simulate a converegecast traffic pattern).

Figure 2.15 represents the impact of an increasing traffic. IEEE 802.11 begins to saturate when we have more than 10 to 15 pps. On the contrary, C-MAC relays more packets with the mechanism based on

Table 2.1: Simulation parameters – default values

Bitrate	11Mbps
Reception threshold	-86dBm
Transmission power	5mW
Frequency	5Ghz (5180→5805)
RTS/CTS	inactive
Packet size	128 bytes
Privileged duration	5ms
space between CTR (CTR_{hops})	3 hops
Number of branches in the k-tree core	5



(a) Throughput (b) End to end delay

Figure 2.15: Random disk topology of 60 nodes with an average degree of 8

privileges. Surprisingly, the delay increases only slightly for a very low traffic (fig. 2.15b). The delay cost to relay packets from one privileged node to another begins quickly acceptable compared to the delay created by collisions.

2.4.6 Limits and Perspectives

In this proposition, we have highlighted that a k-tree core topology is particularly efficient to organize the transmissions in a convergecast MAC layer. The k-tree core proposes a differentiation mechanism for the medium access, a token being propagated distributively.

However, routes must be accurately constructed: they should use in priority the privileged nodes (i.e. the k-tree core). Most of the packets are transmitted by the nodes which own to the clique with the largest weight in the conflict graph. Since these nodes are, by construction, part of the k-tree core, we propose an efficient medium access method.

Some challenges remain still open, and are not addressed in the present proposition. In particular, a radio link presents a certain quality. Thus, we should use a k-tree core using such quality metric to avoid using bad links. A metric to take into account the MAC and routing quality must still be proposed. Besides, this metric would be dynamic. The reconfiguration of the k-tree core is expensive: tokens may be lost, inconsistencies and loop may appear in the topology.

We did not yet addressed the problem of energy saving. In Wireless Sensor Networks, the nodes should implement a low duty cycle ratio, and deafness may arise. However, we may perhaps be able to adapt C-MAC to work with preambles: privileged nodes collect most of the traffic. We may implement one of the following solutions:

- a k-tree core node wakes up when it receives a preamble from its parent. It stays awake until its buffer is empty. The tokens are sufficiently interspaced to avoid the collisions of preambles in the k-tree core;
- the k-tree core nodes maintain a common (synchronized) sleeping schedule to exchange the packets quickly. The normal nodes use preambles: a transmission is more expensive but less frequent.

Finally, multichannel is here limited: the protocol deals only with a limited number of channels. In particular, the load cannot be fairly distributed among the different channels. A bottleneck may appear for the control channel. Thus, how could we distribute more efficiently the load among the different channels while avoiding any deafness problem? We will adresse this topic in the next chapter.

2.5 Conclusion

We exposed here how a node may select its neighbors to improve the performance of the MAC layer. In a first time, we studied the cluster-tree topologie of IEEE 802.15.4: is an association *to the first neighbor* relevant? Through a model and a Mixed-Integer Linear Programming formulation, we can clearly conclude that such association is inefficient concerning the network capacity (i.e. quantity of packets received by the sink). However, we still have to propose an efficient association procedure to fill the gap with the optimal centralized solution.

In the same way, we proposed to structure the network by creating a Weakly Connected Dominating Set (WCDS) to organize the synchronization, pre-requisite when using a short preamble [Pol+04]. A node may save energy by listening to a small number of reference nodes (neighboring dominators from the WCDS). We also addressed the broadcast problem (to neighbors, for discovery and flooding).

Finally, we presented a k-tree core topology very well suite for a network with a convergecast traffic pattern. By using the k-tee core, we allow the implementation of a differentiated medium access to limit the number of collisions. We create branches, constituting *highways* to forward efficiently the packets to the sink. We also presented a routing scheme optimized for this medium access technique. Finally, we proposed a multichannel extension of C-MAC to multiplex efficiently the transmissions.

We have clearly now to extend these solutions so that they perform efficiently *in vivo*, with experimental conditions. In particular, a radio link quality should be estimated and integrated in the structures of topology control. This constitutes a challenge since this estimation is complicated in practice, creating some instability, as we will highlight in chapter 4.

Finally, we did not implement any power adaptation solution, a very common technique in topology control. Increasing the transmission power improves often the radio link quality, but also increases interference. We have rather considered this may constitue a separated problem: the transmission power should be chosen after a neighbor has been selected by the topology control solution. Such approach is easier to implement, but is clearly sub-optimal.

In the next chapter, we will focus on the multichannel problem in general, whatever the scenario we consider is (mesh or sensor).

2.6 Related Publications

Journals

[TD11] Fabrice Theoleyre and Benoit Darties. “Capacity and Energy-Consumption Optimization for the Cluster-Tree Topology in IEEE 802.15.4”. In: *IEEE Communications Letters* 15.8 (2011), pp. 816–818.

[The11] Fabrice Theoleyre. “A Route-Aware MAC for Wireless Multihop Networks with a Convergecast Traffic Pattern”. In: *Computer Networks* 55.3 (2011), pp. 822–837.

Conferences

[Bac+10] Abdelmalik Bachir, Fabrice Theoleyre, Andrzej Duda, and Kin K. Leung. "Energy-Efficient Broadcasts in Wireless Sensor Networks with Multiple Virtual Channels". In: *Wireless Communications and Networking Conference (WCNC)*. IEEE. Sydney, Australia, 2010.

[The+10] Fabrice Theoleyre, Abdelmalik Bachir, Nesrine Chakchouk, Andrzej Duda, and Kin K. Leung. "Energy Efficient Network Structure for Synchronous Preamble Sampling in Wireless Sensor Networks". In: *International Conference on Communications, (ICC)*. IEEE. Cape Town, South Africa, 2010.

Book Chapters

[NAT12] Benoit Darties Nazim Abdeddaim and Fabrice Theoleyre. "Wireless Sensor Networks: Technology & Applications". In: Intech, 2012. Chap. Bandwidth and Energy Consumption Tradeoff for IEEE 802.15.4 in Multihop Topologies. DOI: 10.5772/48295.

Chapter 3

How could we exploit efficiently several channels in parallel?

In a wireless multihop network, we quickly face to the problem of capacity and reliability. In particular, CSMA-CA of IEEE 802.11 leads to several fairness and performance problems [Cha+05]. When the congestion begins to appear, many packets are dropped, the delay increases drastically, the fairness falls, the throughput of the flows passing through the bottleneck decreases very fast.

We are convinced that using several channels in parallel should solve some of these problems. Multichannel asset is not restricted to using more bandwidth, it also solves some of the fairness problems appearing suddenly in the MAC layer. By multichannel, we consider here only the usage of multiple disjoint frequency bands.

However, multichannel is complicated to implement in practice, mainly because of the deafness problem: the emitter must know a priori the channel used by the receiver. Else, the packet is lost because the listener is *deaf*. We will see in this chapter how we may solve this deafness problem.

We focus here on the multichannel problem in 3 different scenarios (from the less to the most constrained one), leading to 3 distinct solutions:

1. a mesh network with multi-radio nodes: each wireless router has several IEEE 802.11 interfaces, able to switch dynamically from one channel to another. We will see that this configuration causes problems of neighbor discovery, broadcast optimization, and channel assignment.

2. a mesh network with single interface nodes: how does a node with one unique interface multiplex its transmissions over different channels without deafness? We propose that some of the nodes switch dynamically their channel while the other ones stay static. This organization greatly improves the throughput.

3. a wireless sensor network using IEEE 802.15.4: when we take into account energy efficiency, how could we transform IEEE 802.15.4 to make it multichannel?

In this chapter, we will use indistinctly the terms *interface* and *radio* because we consider only pure wireless mesh routers.

3.1 IEEE 802.11s fundamentals

The standard IEEE 802.11s has been proposed in 2011 to handle wireless IEEE 802.11 multihop networks [802b]. The core is constituted by wireless routers, denominated *Mesh STA* [Car+11] (figure 3.1). If these routers are interconnected to the Internet, they are *Portal* (MPP). They may also offer a connectivity to clients, being in this case a classical IEEE 802.11 access point (AP).

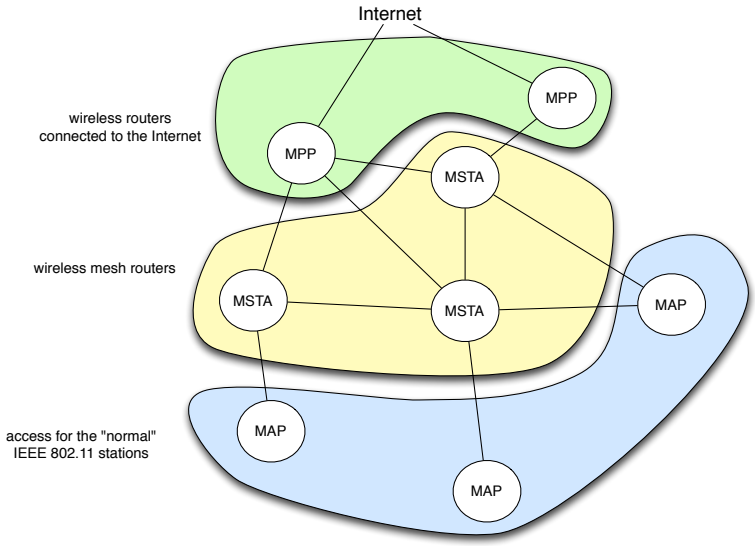


Figure 3.1: Topology created by IEEE 802.11s

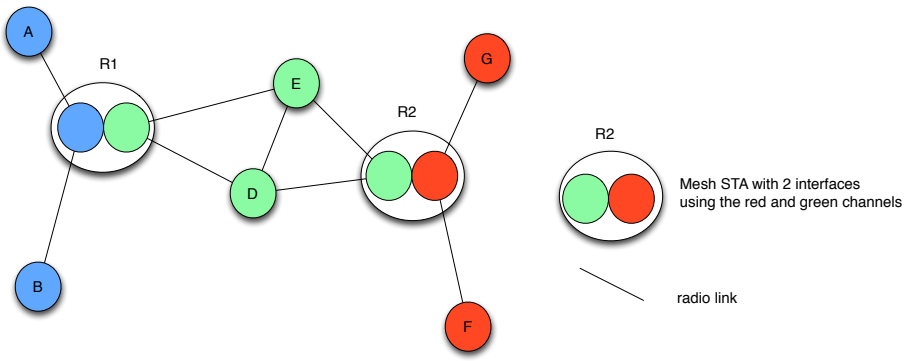


Figure 3.2: Topology created by IEEE 802.11s in multichannel when using several interfaces

Possibly, all the Mesh Portal may be interconnected to constitute one single LAN. This interconnection is similar to the backbone connecting the IEEE 802.11 Access Points (i.e. the WDS).

The standard offers a single multihop LAN connectivity. IEEE 802.11s proposes its own routing (layer 2) protocol. Hybrid Wireless Mesh Protocol (HWMP) proposes 2 modes: in proactive mode, it creates a tree rooted in the portals. On the contrary, the reactive mode constructs the routes on demand, similarly to AODV [Per+03].

IEEE 802.11s uses by default the *Airtime Link Metric*. The cost of the link is the time before an acknowledgment is received for a frame of 1,024 bytes. The metric takes into account the bitrate, the physical headers, and the packet delivery ratio of the link. The standard lets the implementation method unspecified.

To limit the contention, the wireless routers reserve some periodical transmission opportunities (MCCA), during which the medium contention is limited. However, all the mechanisms to detect the congestion and to select the most accurate transmission opportunities are also let unspecified.

The designers of IEEE 802.11s have focused on the single interface case. However, some multi-radio nodes may be integrated by using them as bridges between two IEEE 802.11s LANs [Hie+10]. We may consider the network has a collection of single-channel islands, interconnected with multiradio bridges. Figure 3.2 illustrates such topology. The router R1 serves as a bridge between the green and blue LANs.

Mechanisms are provided in the standard to announce a channel switching to maintain a connected topology.

The channel assignment strategy proposed initially to assign a priority to each channel. Then, a node with k interfaces used the k channels with the largest priority. In the final version, this assignment seems have been withdrawn.

However, considering two interfaces as 2 *virtually* distinct LANs is sub-optimal. Michel et al. [Mic+13] have proposed for instance to share MAC information between all the interfaces (neighborhood and routing tables) to optimize the forwarding. This method only slightly improves the load balancing feature.

3.2 Multiradio Mesh Network

We focus here on the mesh networks with multiradio wireless routers. These routers must forward the traffic from final terminals to the portals. We consider only the core network, and exclude deliberately the last hop wireless access.

Scientific challenge

In multiradio multichannel mesh networks, how could we provide an efficient broadcast primitive and how could we assign efficiently the channels to work with IEEE 802.11s ?

All the work related to multiradio multichannel wireless mesh networks is part of the Ph.D. thesis of **Carina Teixeira de Oliveira** I had the great chance to co-advise with Andrzej Duda (LIG, oct. 2009 - oct. 2012).

3.2.1 Classifying the existing multichannel strategies

We first proposed a classification of the strategies exploiting several interfaces in a mesh network [Oli+11a]. We have to assign a set of channels to each interface, following one of these approaches:

Static: one fixed channel is assigned to each interface in the network;

Dynamic: one interface has to switch dynamically the channel it uses over time;

Hybrid: some interfaces are static while the other ones are dynamic.

In any case, we must avoid the deafness problem, i.e. the emitter must know the channel used by the receiver.

Besides, the algorithm must decide which channel to assign. The assignment may be:

with a common channel: we must maintain the connectivity. A simple strategy may consist in using the channel k for the kth interface. However, the number of interfaces is practically low: the highest channels are consecutive under-exploited;

pseudo-random: to distribute the load over all the channels, a node may compute a hash of its identifier modulo the number of channels. This value gives the channel to use [KV05]. However, maintaining the connectivity is in this case only probabilistically guaranteed;

adaptative: the node measures locally the load of each channel and selects the less loaded one.

Many propositions exist in the literature, mixing these different approaches to exploit several interfaces (static / dynamic / hybrid) and to assign channels. So and Vaidya [SV04] has for instance proposed to use a common control channel to make a reservation for data transmissions, achieved over different channels (i.e. hybrid interfaces, with a common channel assignment for the static interface, and an adaptive assignment for the other ones).

3.2.2 Neighborhood discovery

In multihop wireless networks, broadcast is essential: it is widely used to disseminate control information to the neighbors, to estimate the radio link quality, to construct routes. When only one channel is used ant the nodes never sleep, one single transmission is sufficient to cover all the neighbors. However, is that similar when multichannel is adopted? Because of the deafness, one single transmission may be insufficient. Thus, we have focused on proposing an efficient broadcast primitive, whatever the assignment strategy is.

Scientific challenge

whatever the assignment is, how could we discover efficiently a neighbor in a multichannel environment?

In a mesh network, we must take into account the fact that radio transmissions are unreliable. A neighbor may not receive a broadcast packet even if it is listening to the correct channel. While IEEE 802.11 proposes to use the lowest bitrate (i.e. the *basic rate*) with the most robust modulation for broadcast transmissions, we cannot assume a perfect delivery ratio. We could make the transmission reliable by transforming the broadcast into unicast: we duplicate the packet for each neighbor. The delivery would be reliable since unicast packets can be acknowledged. However, this technique would require a huge number of packets and would not exploit the broadcast nature of radio transmissions.

We have consequently proposed algorithms for broadcasting a packet to neighbors, whatever the assignment strategy is [Oli+11a]. We assume a node has already constructed its neighborhood table and has an estimation of the packet delivery ratio to each of its neighbors: this metric is widely used for routing. The source must *cover* each of its neighbors with a probabilistic guarantee (i.e. the probability that this neighbor receives the packets is greater than a threshold value). We dismiss the neighbors with a too low packet delivery ratio: anyway, they would not be chosen by the routing protocol to forward packets.

We propose the following heuristics for each scenario:

a common control channel: the source must transmit several copies of the packet on the control channel. The number of copies is computed to *cover* the weakest neighbor;

static assignment: we propose to use an approach inspired from the multipoint relays (MPR) [CJ03b]. For each iteration, the source selects greedily the channel covering the largest number of uncovered neighbors. It stops the transmissions when all its neighbors are covered with a given probability;

dynamic interfaces with low frequency hopping: we adapt the previous version to deal with frequency hopping. The source constructs the schedule of frequency hopping for all its interfaces, with a set of timeslots and channels for each interface. Then, the source selects greedily the pair timeslot / interface to cover the largest number of neighbors.

Let consider the dynamic interface assignment to illustrate the third heuristic (Fig. 3.3). When we have a channel switching for an interface, a new timeslot is created. We represented the list of neighbors covered by $V1$ during each of its slots for each of its interfaces. In our example, $V1$ will select for instance the slot 1 and interface 1 to cover its neighbors $V3$ and $V4$, and the timeslot 1 over the third interface to cover $V2$. The number of transmissions strongly depends on the radio link quality of each of these neighbors.

3.2.3 Connectivity in multichannel

When one single channel is used, the connectivity graph is dense: every node in the radio range receives a packet (with a certain probability). In multichannel, the connectivity graph is sparser:

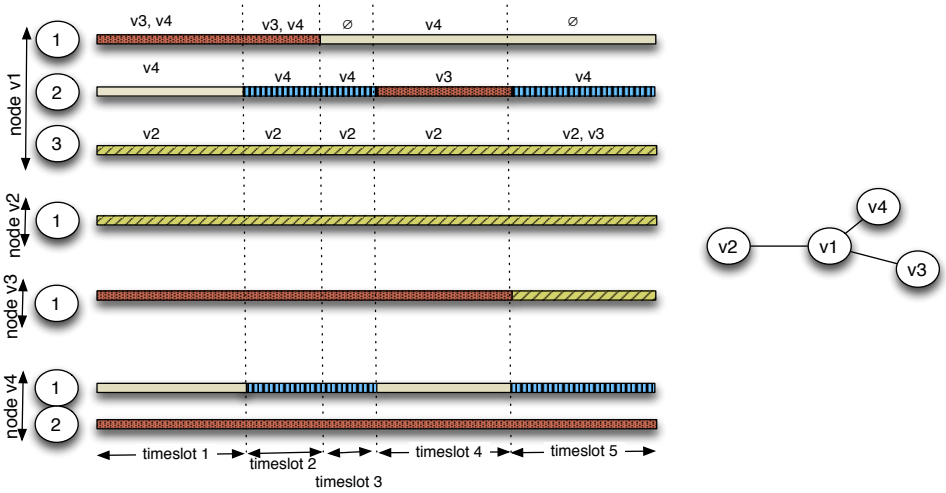


Figure 3.3: Broadcast with a dynamical channel assignment

- two nodes with static interfaces and no common channel are deaf and should pass through an intermediary node to exchange packets;
- when using frequency hopping, two nodes are neighbors during a reduced time.

Surprisingly, the density of the graph was seldom studied although it has a strong impact on the network capacity and the discovery time.

Scientific challenge

What is the density of the connectivity graph and what is the discovery time in a multichannel environment?

We have computed analytically several metrics for each assignment strategy [Oli+11b] :

Connectivity : the size of the largest connected component. This component may not include all the nodes when for instance the pseudo-random strategy based on a hash value is used;

Density: the average number of links per node. With frequency hopping, a radio link is weighted by the ratio of time during which it exists.;

Rendez-Vous Time: the average time before a neighbor is discovered.

Let consider the simplest scenario, with a static assignment and a common control channel (the interface k uses the channel k), we have[3]:

- the graph is connected, at least through the first interface (the number of interfaces may differ among the nodes). The connectivity is 100%;
- the density is maximal since each neighbor in *single channel* is also neighbor in multichannel, through each interface;
- discovery is trivial using for instance the first interface.

However, this scenario also implies more contention and a bad distribution of the load among all channels if we have more channels than interfaces. We have consequently also evaluated the network capacity of the different strategies.

[3]other strategies are described in details in [Oli+11b]

3.2.4 Network Capacity

The channel assignment originally proposed by the IEEE 802.11s working group was approximatively similar to the *common channel* assignment when all the nodes have the same number interfaces. While many assignment strategies have been already proposed, we aim here at comparing objectively their performance: what network capacity do they provide? Besides, we aim also at measuring their interaction with the routing and MAC protocols as proposed by IEEE 802.11s. Indeed, our model makes some assumptions to make the problem tractable. What does occur if we dismiss these assumptions?

Scientific challenge

Could we evaluate analytically the network capacity offered by the different assignment strategies? How do they impact practically the behavior of IEEE 802.11s?

Capacity model

We have first presented a MILP formulation to quantify the capacity associated to each assignment strategy [Oli+12; Oli+11c]. If the strategy remains unspecified in the MILP, we have a classical optimization problem, and the solver provides the optimal solution.

Subramanian et al. [Sub+08] have chosen to minimize interference. On the contrary, we chose to maximize directly the throughput, i.e. the aggregated bandwidth assigned fairly to each flow. We consider each router generates one flow, relayed toward the mesh portal. We consider only a perfectly fair scenario. Considering only interference is too restricted: the traffic is not uniformly spatially distributed, and the routers close to the sink have more traffic to forward.

We considered the general case with multiradio nodes and each interface may switch dynamically its channel. We used the notion of *timeslots*: an interface stays static over a channel during the timeslot. We translated all the constraints into linear inequalities:

flow conservation: every packet which is received by a node is forwarded by the router. Besides, the portal *consumes* all the traffic;

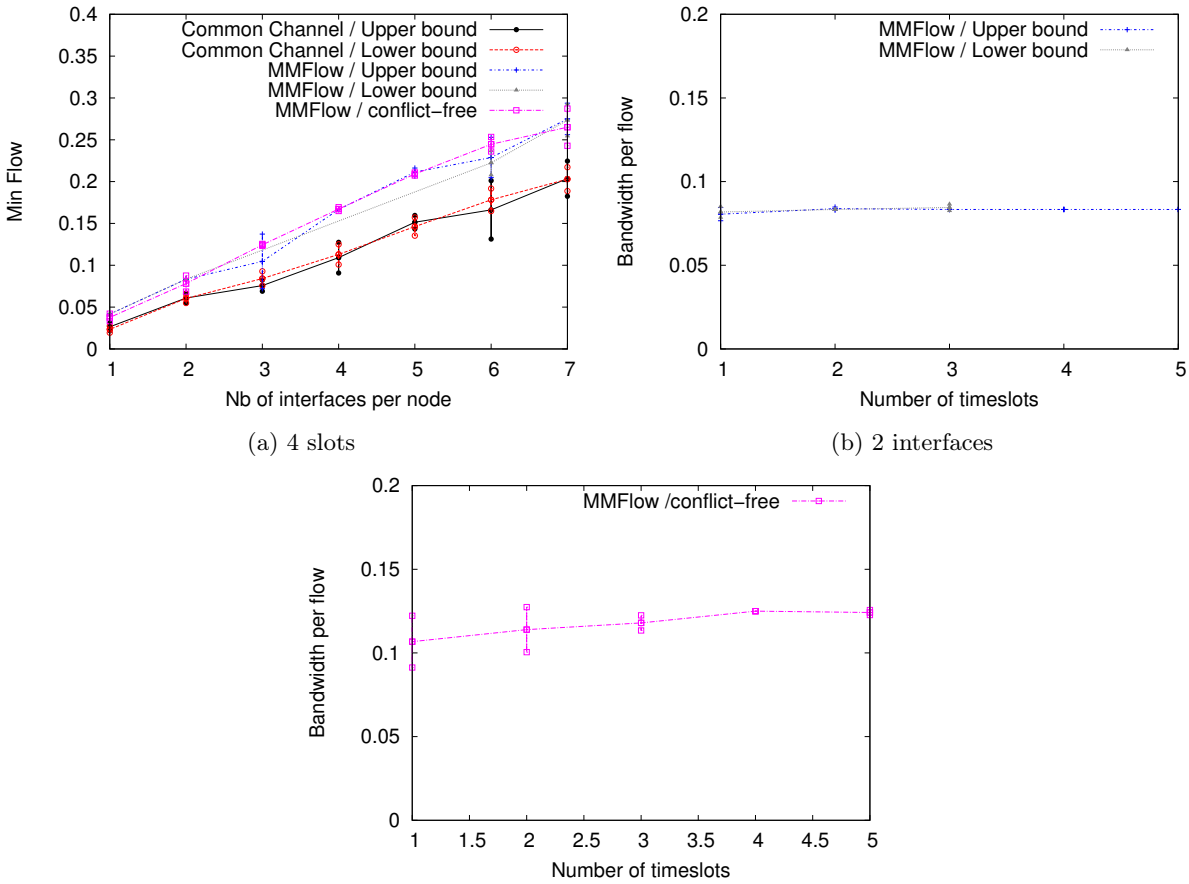
mutichannel aggregation: the traffic of a link is transmitted over all the channels and timeslots of one interface. Besides, the traffic cannot be relayed if the node is inactive during a given timeslot and channel;

interface number: the number of channels used at a given instant by a node is less than or equal to the number of its interfaces;

multi versus single path: we may forbid mutipath to simplify the design of the routing protocol;

bandwidth sharing: we must define rules to describe the local bandwidth sharing. We have the following bounds:

- **upper bound:** we consider the medium is able to regulate ideally the contention. We just have to verify that inside a group of interfering links, the traffic they have to forward is less than the radio bandwidth. This constitutes an upper bound since such optimal MAC strategy may never exist;
- **lower bound:** we reference a sufficiently large number of independent sets of radio links in the conflict graph (i.e. radio links which do not mutually interfere). Then, we assign a ratio of the radio bandwidth to each independent set. In this set, all the corresponding radio links are authorized to transmit simultaneously. This throughput may be achievable when using for instance the MCCA mechanism of IEEE 802.11s, and when assuming all the nodes are synchronized.



(a) 4 slots

(b) 2 interfaces

(c) 2 interfaces

Figure 3.4: Numerical results (25 nodes, 10 channels)

no conflict: we forbid two interfering radio links to use the same channel simultaneously. The MAC layer is in this case much simpler to design: we have no contention. Through this strategy, we aim at quantifying the problems created by the collision resolution.

The complete model and associated equations are described in details in [Oli+12].

Numerical results We compared the following strategies:

- Common channel / Upper & Lower bounds: the channel k is assigned to each kth interface;
- MMFlow / Upper & Lower bounds: the MILP formulation provides the optimal assignment and routes;
- MMFlow / no-conflict: the MILP formulation provides the assignment when no conflict is authorized.

We used here a custom simulator generating a unit disk graph, with on average 7 neighbors, using 10 channels. We consider the interference range is twice the radio range [Iye+09]. We will describe later the results we may obtain with more realistic assumptions through simulations.

In a first time, we verified the network capacity is really different according to the channel assignment strategy (Figure 3.4a). Thus, a gap to fill with IEEE 802.11s remains important.

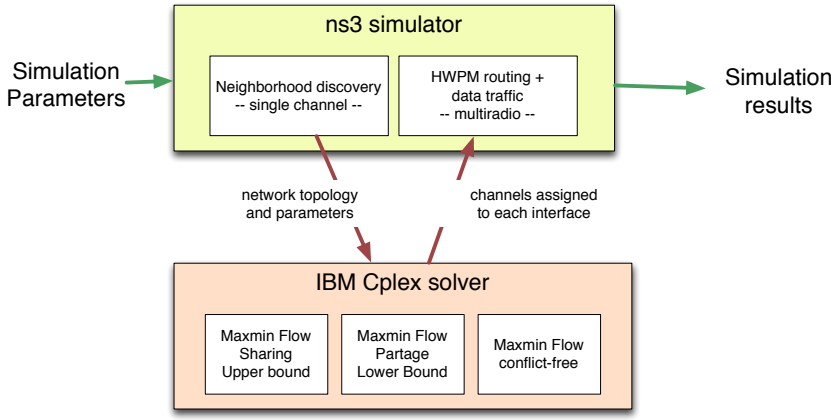


Figure 3.5: Interactions with Cplex and ns3

Interestingly, we can note that in figure 3.4b that the capacity is only slightly impacted by the number of timeslots: a static assignment would be sufficient. We can also make the same remark when we adopt the conflict-free assignment: the capacity increases only marginally (fig. 3.4c).

Practical impact on IEEE 802.11s

Finally, we aimed at validating these results on realistic scenarios. We have interconnected our MILP resolution with ns3, and simulated the complete behavior of IEEE 802.11s with the default radio propagation model in ns3.

We have finally the scenario presented in figure 3.5:

1. We execute a neighborhood discovery to discover the radio topology we would obtain with one unique channel;
2. We inject the topology into Cplex so that it provides the assignment for the configured strategy;
3. We use this channel assignment with IEEE 802.11s.

To stay concise, we present only Figure 3.6 representing the real capacity of the different strategies. We can verify that we practically increase the network capacity compared to a *common channel* assignment, and this impact is more important when we have more interfaces. Besides, the conflict-free strategy demonstrates its practical interest: it permits to obtain a larger network capacity because it limits in particular the number of collisions between data and control packets. We have been able to highlight some instability problems in the creation of routes: collisions tend to disrupt the control plan.

3.2.5 Limits and Perspectives

We tried here to characterize the multichannel multiradio mesh networks. After having presented a taxonomy of the different interface and channel assignment strategies, we proposed an efficient broadcast primitive at the MAC layer. We analyzed also the impact of the channel assignment on the network capacity: our formulation is sufficiently general to compare any solution. We completed this analysis by simulations, evaluating the practical impact with more realistic models.

This work is a first step toward understanding this kind of network. In particular, we highlighted that conflict-free assignment performs very well practically: the bandwidth wasted by collisions is reduced, and the raw network capacity is only slightly impacted. We still have to propose a strategy exploiting the MCCA mode (a pair of nodes may reserve some transmission opportunities).

The MILP formulation remains complicated, and the computing time increases exponentially with the number of timeslots and the network density. As we noticed, the number of timeslot only slightly impacts the capacity. However, it would be relevant to accelerate the resolution.

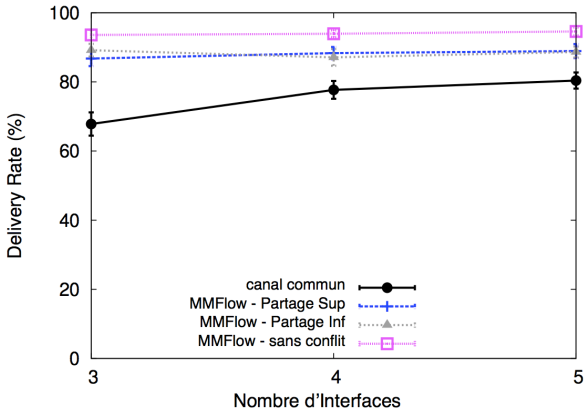


Figure 3.6: Packet delivery ratio depending on the channel assignment strategy

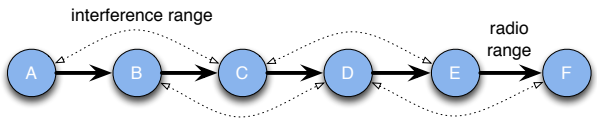
We also isolated some instability problems during the simulations. In HWMRP, control and data packets collide with each other, and paths are continuously repaired. This instability is prejudicial to the network.

Finally, we guess multipath could maximize the throughput in multiradio multichannel mesh networks. Indeed, the traffic is often not uniformly spatially distributed: multiple paths help to spread the load. Besides, wireless mesh networks may interconnect a collection of WSN islands for the new Internet of Things. The border router would not be the unique entry point for traffic (i.e. no convergecast). In such scenario, a path per flow would reduce the amount of interference if the paths are well chosen. We have started to explore this topic with Carina Teixeira de Oliveira by estimating the residual bandwidth, coupled with a reactive routing solution. However, her postdoctoral position has temporarily stopped with research topic.

3.3 Single radio multichannel mesh networks: Molecular MAC

We now consider a more constrained network, with single interface routers. IEEE 802.11 is well-known to perform poorly in this situation [Cha+05].

Indeed, a multihop topology implies an asymmetrical view: two emitters have not the same perception of the channel activity. We have to face to hidden, blocked or exposed terminals [Cha+05; IR06].



(a) single channel

(b) multichannel

Figure 3.7: Chain topology

Let consider the chain topology, as illustrated in figure 3.7a. We assume that a pair of nodes 2 hops far interfere with each other (discontinuous links). When A transmits a frame to B, C is blocked. The throughput decreases quickly when the number of nodes increases in this chain (cf. Figure 3.8 and [Cha+05]).

On the contrary, if interfering links use different channels, we may multiplex the transmissions (cf. transmissions A-B and C-D in figure 3.7b). We obtain a larger throughput. Using several channels

increases also the throughput in several pathological IEEE 802.11 scenarios. When 3 pairs are contending with each other as illustrated in figure 3.9, the extreme pairs monopolize the medium [Cha+05]: the pair in the middle never observes an idle medium. If the middle pair use a different channel, we don't have such problem.

However, a node with one single interface may suffer from deafness: the emitter must know the channel used by the receiver. Molecular MAC proposes an efficient method to implement a multichannel MAC without deafness.

Two main families of protocols exist in the literature. MMAC (Multi-Channel MAC) proposes to establish periodical Rendez Vous points [SV04]. During these RDV, all the nodes must exchange control packets on a dedicated channel to decide which channels will be used later for the data transmissions. For instance, MMAC reduces the probability that all the emitters use the same channel in the 3 pairs scenario.

SSCH (Slotted Seeded Channel Hopping) [Bah+04] proposes a TDMA approach. Each node choose a pseudo-random sequence of frequency hopping, and published the seed used for this sequence. If a neighbor knows the seed, it is able to reconstruct the schedule, and to know the channel used by the receiver. However, two neighboring nodes may have only a few common slots using the same channel at the same instant. The collision probability is reduced in the same proportion as the bandwidth.

Scientific challenge

How could we exploit efficiently a network of nodes with one unique interface and decrease, or even remove the pathological cases of IEEE 802.11 in multihop?

3.3.1 Molecular MAC

We have proposed Molecular MAC [Nas+09; Nas+08] which presents the following properties:

1. no deafness is possible;
2. transmissions are multiplexed over different channels;
3. contending transmissions are solved with the cellular IEEE 802.11 case, removing the hidden, terminal and exposed terminal problems;
4. the network is organized: some nodes stay static on a channel while the other ones continuously switch from one channel to another to authorize multihop flows.

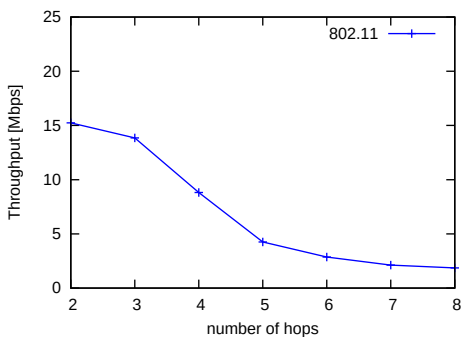


Figure 3.8: Throughput in a chain of variable length (in hops)

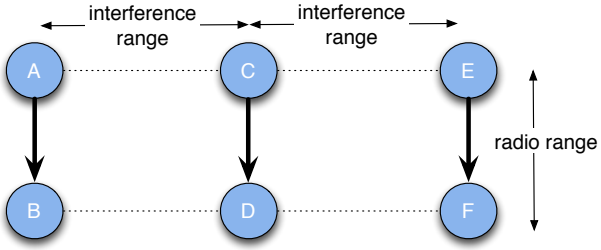


Figure 3.9: 3 pairs in single channel

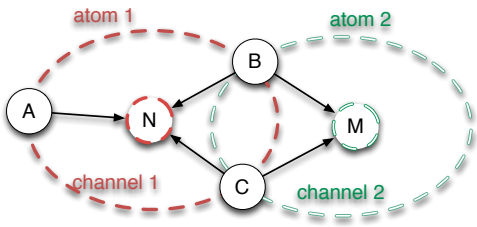


Figure 3.10: 2 atoms sharing 2 electrons

We adopt an analogy with a *molecule* to organize the network (figure 3.10). One atom is the basic element: it is composed of a *nucleus*, using a static channel to communicate with a collection of *electrons*, direct neighbors. The set of atoms form a molecule. The electron which participate to several atoms interconnect them to offer a multihop connectivity.

In figure 3.10, both atoms N and M use disjoint static channels. On the contrary, the electrons B and C own to 2 atoms, and switch from the cannel 1 to 2 and vice versa). We remove the deafness problem since we authorize only the communication between one electron and one nucleus.

To operate without interference, two interfering atoms should use different channels. Besides, we use the nuclei as a kind of *virtual access points*: they collect the traffic from their electrons and forward it. In particular, two electrons must pas through a common nucleus to exchange packets. Else, we would have the deafness problem: there is no way to know a priori the channel used by an electron.

Deafness avoidance

We solve the deafness problem:

- only the communications (nucleus $\leftrightarrow$ electron) are authorized;
- when an electron has a packet to send, it executes CSMA-CA. It knows the channel used by the nucleus (static);
- inversely, a nucleus must notify its electrons about the pending packets. An electron must listen periodically to the atoms it owns to. When an electron is notified, it sends a `Clear To Send` to let the nucleus know it is ready to receive the buffered packets.

Notifications

A nucleus notifies an electron following one of these approaches:

1. the list of pending destinations is piggybacked in the data packets transmitted by the nucleus;
2. if no activity is present during T_b, the nucleus sends periodically `beacons` piggybacking the list. In our simulations, we chose to generate a `beacon` if the medium is idle during at least 5 ms.

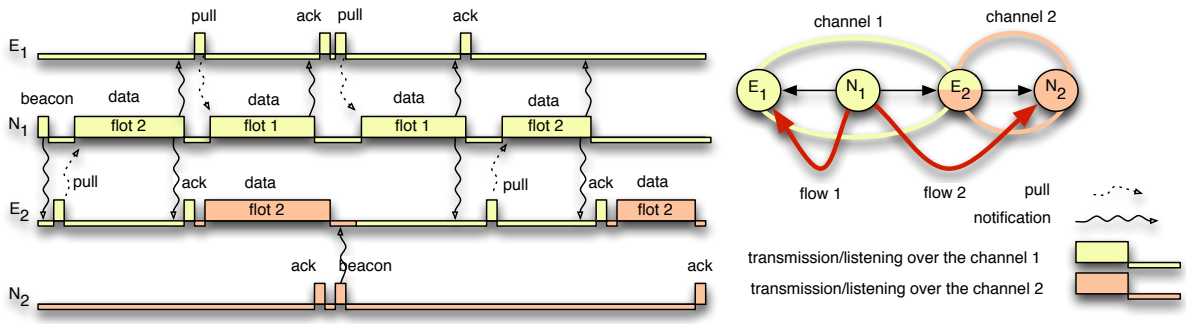


Figure 3.11: Pull mechanism and notifications for the packets forwarded between E_1 and N_2.

If the medium is sufficiently loaded, no `beacon` is generated.

An electron which owns to several atoms should avoid a starvation. An electron must change its channel at least every T_N to collect the notifications of each of its nuclei. Besides, it chooses randomly to either send a buffered frame or to gather a packet from the nucleus.

Figure 3.11 illustrates this pull mechanism. The electron $E1$ listens continuously on the channel 1 and receives all the notification of its nucleus. On the contrary, $E2$ has to switch continuously, sending a `Clear To Send` when it is notified by $N1$ that some packets are buffered for it.

Optimization: quick reply

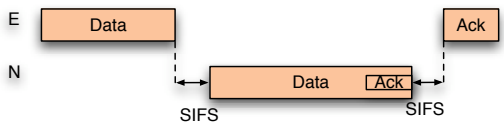


Figure 3.12: Quick reply for a transmission electron→nucleus

To improve the throughput, we propose a quick reply mechanism. When an electron sends a data packet to the nucleus, it may reply by concatenating both the ack and some buffered data packet. We remove in this way the need of specific `Clear To Send`. Figure 3.12 illustrates this sequence of 3 frames `data/data/ack`,.

Multiradio

While Molecular MAC was originally designed for single interface nodes, it may also deal with multiradio routers. A node has just to assign a role per interface, offering a different connectivity to each of its neighbors. However, the routing protocol must choose optimal routes, taking into account the roles for each interface. For instance, it is more efficient to exploit a link from an electron to a nucleus than the other direction: no notification is required.

Performance evaluation

Because of conciseness, we present here only the results obtained by simulations with a random topology of 50 nodes. We compared:

Molecular MAC

MMAC: the protocol uses a periodical RDV to reserve the channels used after for the data transmissions;

80211: IEEE 802.11 with one single channel;

Table 3.1: Simulation parameters

Duration	240s
Bitrate	54Mb/s
Reception threshold	-86dBm
Transmission power	5mW
RTS/CTS	désactivé
Buffer size	256 kbytes
Packet size	1,500 bytes
T_b: max time between two notifications	5ms
T_N: max listening time on one channel	10ms
Hello interval (Molecular)	1s
Beacon Interval (MMAC)	25ms
ATIM Window (MMAC)	5ms

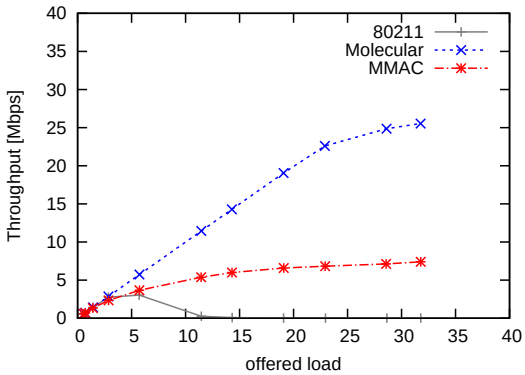


Figure 3.13: Aggregated throughput

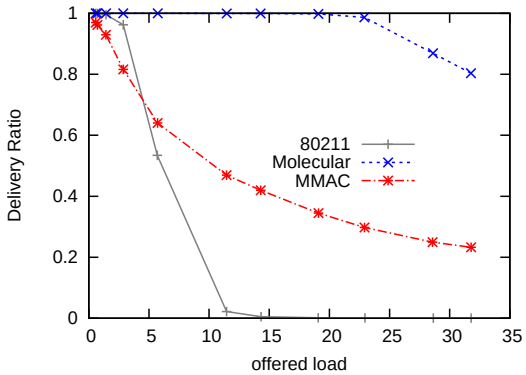


Figure 3.14: Packet delivery ratio

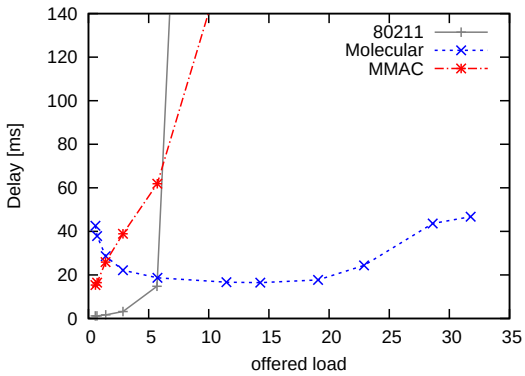


Figure 3.15: End to end delay

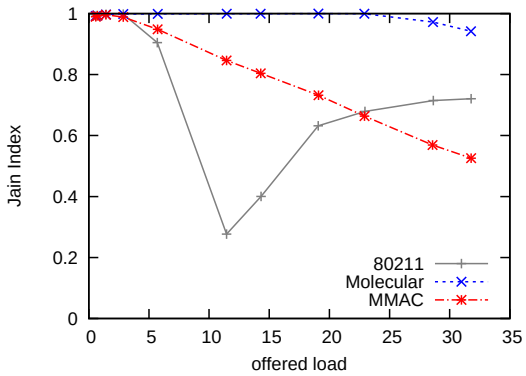


Figure 3.16: Jain index (fairness)

Figure 3.17: Random topologies of 50 nodes uniformly distributed in a disk of radio 270 m

The simulations are conducted with opnet, with the default parameters illustrated in table 3.1, using the IEEE 802.11a MAC layer.

Figure 3.17 illustrates the results obtained by simulations. We verified that IEEE 802.11 with one unique channel performs very poorly, even with a low traffic. MMAC saturates very quickly and does not succeed to exploit all the channels. In particular, the delay increases drastically, highlighting the problems created by forwarding a multihop flow.

On the contrary, Molecular MAC improves the throughput, even with a larger traffic. The throughput is almost multiplied by 5 compared to MMAC. The end to end delay is larger for a low traffic: the notification through `beacons` require some time (5 ms per hop). On the contrary, a larger traffic tends to decrease the delay, highlighting the interest of Molecular MAC.

3.3.2 Molecule construction

We did not previously explained how we should construct the molecule (i.e. assign the roles). We must maintain the following properties:

- maintain the connectivity, since only the transmissions between a nucleus and an electron are authorized;
- maximize the capacity;
- limit the route length which may have an impact on the reliability (path stretch factor).

Scientific challenge

What heuristics may assign a role for each node while maximizing the fair throughput in Molecular MAC ?

All the work related to the molecule construction is the topic of the postdoc of **Benoit Darties** (LIG, 2008 - 2009).

Construction of a weakly connected dominating set

When we take a closer look at the molecule structure, we can note that in reality, it corresponds to a particular Weakly Connected Dominating Set (WCDS). A WCDS is constituted by a set of dominating vertices, i.e. every non-dominating vertex is neighbor of a dominating vertex in the graph. Besides, the graph comprising only the edges with at least one dominating node is still connected.

A molecule is a WCDS with an additional contraint: the graph comprising the edges with exactly one dominating node is still connected. In other words, we may remove any edge between two dominating nodes: the graph is still connected.

We should minimize the number of nuclei to limit the amount of interference: two interfering nuclei must use different channels while the number of channels is finite. This problem is related to construct a WCDS with a known cardinality, which is NP difficult [Dun+97]. We proposed the following strategies: [The+09b] :

Independent Dominating Set: nuclei are chosen randomly, while their neighbors become their electrons. This approach does not guarantee the connectivity. However, the probability the graph is connected increases with the density (it is close to 99% with an average degree of 10 neighbors);

Spanning tree: a tree is first constructed distributively. Then, all the nodes with an even depth become nuclei. We also proposed rules derived from the algorithm [WL01] to reduce the number of useless nuclei;

MILP formulation: to have a clear comparison, we proposed a MILP formulation of the network capacity maximization problem. This centralized approach provides an upper bound.

Numerical results highlight the fact that these distributed heuristics lead to a connected structure but perform quite poorly for the capacity.

We have consequently proposed a *divide-and-conquer* solution, named *potatoes*[Dar+09a]: we create distributively a spanning tree, and some clusters along this tree. The clusters are created hierarchically, based on the depth in the tree. The MILP formulation is then applied inside each closer by the leader: it assigns the roles to each cluster member. We assign carefully the roles for the border nodes, to interconnect properly the clusters.

2-approximation

We aimed at going further to offer a guarantee of performance. We remarked that the molecule is a particular WCDS we designated *reversible*: the roles between nuclei and electrons may be exchanged, while the structure keeps its WCDS property [Dar+09b] In particular, we aimed at maximizing the connectivity, i.e. the number of radio links which are still exploitable with Molecular MAC.

After having proved the problem of such maximization is NP-complete, we proposed a 2-approximation. Intuitively, this structure is very similar to a bipartite graph. We decide iteratively the role for each by greedily placing the node in the dominating or dominated set while we maximize the number remaining radio links during each step.

Finally, we transformed this heuristic into a distributed version, integrated in a protocol. We elect a leader (i.e. the gateway, or any other node), and each node selects greedily its role, maximizing the number of remaining links with its neighbors. Time-stamping permits to detect inconsistencies when two nodes take a decision simultaneously.

This approach maximizing the number of radio links in the molecular structure finally improves the throughput, as we highlighted in simulations [Dar+09b].

3.3.3 Neighborhood discovery

A novel node must be able to discover its neighborhood and to be inserted in the molecule. We proposed a neighborhood discovery process adapted to Molecular MAC [Abd+10]. Besides, we also coupled a distributed solution to assign a channel for each nucleus while minimizing the interference in the network.

We studied analytically the average discovery time, and the ratio of time dedicated to neighborhood discovery and activity measurement.

3.3.4 Limits and Perspectives

We presented here Molecular MAC: it removes the pathological cases of IEEE 802.11 in multihop topologies. By organizing properly the network into a molecule, we maintain some nodes static while the other nodes dynamically tune their channel without deafness. Some MAC mechanisms (notification, indirect transmission) enable one electron and one nucleus to communicate in both directions.

We also proposed heuristics to assign distributively the roles (nucleus / electron) to each node. This problem is related to what we call a *reversible WCDS* with a maximization of edges. This WCDS problem is largely used in the literature for routing in WSN [Cha+12], or flooding in mesh networks [Cho+06]. We guess these propositions present a large interest, and are not restricted to Molecular MAC.

We did not here take into account the radio link quality. We should modify the WCDS structure to use a weighted graph. However, this problem is, to the best of our knowledge, untreated in the literature.

While some researchers reported the channel switching time may be very low for IEEE 802.11abg wireless cards ($< 30\mu$s), we should now evaluate experimentally Molecular MAC. Such experiment is not an easy task since Molecular MAC modifies several mechanisms of IEEE 802.11:

- including the list of pending destinations in data packets is simple to implement: it may be pre-computed;
- the `Clear To Send` may be re-used from IEEE 802.11 since it has the same role. However, the reply to the CTS is more complicated to implement since the nucleus has not yet prepared the associated data packet. It could be possible to implement such mechanism by forcing the electron to stay on

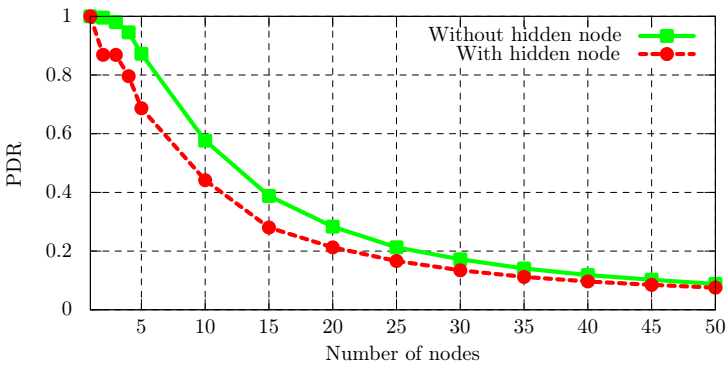


Figure 3.18: Throughput achieved by IEEE 802.15.4-2006 in beacon-enabled mode with a star topology, simulations with wsnet

the same channel for a sufficiently long time. In this way, the nucleus may be able to prepare the data packet. However, this would consume some bandwidth, and would increase the number of collisions (the nucleus would not have anymore a reserved medium for the reply);

- the quick reply mechanism would surely be complicated to implement since it requires a very short timing.

Finally, we focused on the MAC layer features: how can the transmissions be efficiently multiplexed? However, a routing protocol exploiting this topology remains to be proposed. We only used in the simulations the shortest routes in number of hops, and we did not take into account the radio link quality. A protocol should present the following properties:

- balance the load among atoms;
- avoid to use the same links to interconnect different atoms;
- implement a multipath scheme to spatially distribute the load among interfering flows.

3.4 Wireless sensor networks with one single interface and constrained in energy: multichannel IEEE 802.15.4-2006

After having focused on the mesh networks, we aimed at studying the networks with an energy constraint. The IEEE 802.15.4-2006 standard exists currently to regulate the medium access for low power networks. We briefly described its behavior in the chapter 2.1.

However, the medium access of IEEE 802.15.4-2006 is very agressive. Indeed, all the nodes wake-up simultaneously, at the beginning of the active period and contend for the medium access. They turn off their radio during the backoff, and may drop the frames if the medium is sensed busy twice (default value of the parameter `macMaxCSMABackoffs`). Several packets are lost at the beginning of the active part, even if the buffers are empty at the end: the nodes cannot exploit efficiently the radio bandwidth. IEEE 802.15.4-2006 performs very poorly in a star topology when the number of nodes increases, as illustrated in figure 3.18.

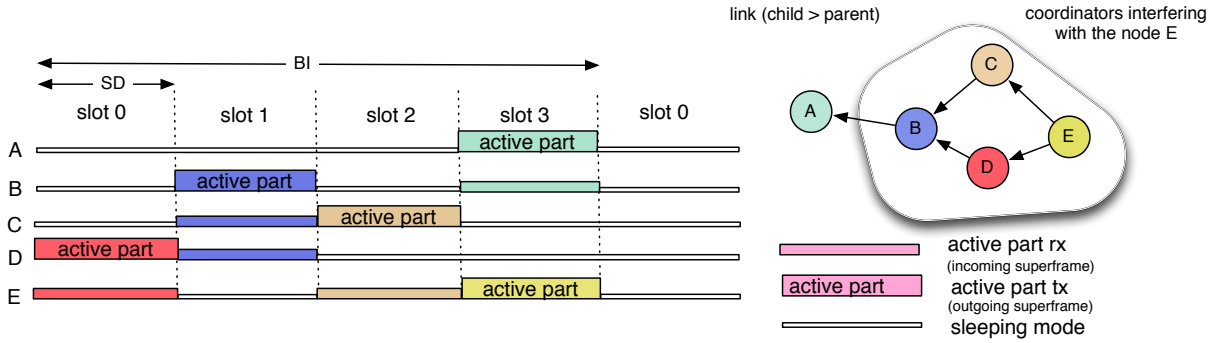


Figure 3.19: Scheduling of the active parts in IEEE 802.15.4-2006

Scientific challenge

Is it possible to exploit a multichannel version of IEEE 802.15.4 to limit interference and collisions among coordinators? Besides, how should we adjust the parameter values of the protocol so that a node always operate close to the optimal conditions?

All this work related to IEEE 802.15.4 represents the end of the Ph.D. thesis of **Nazim Abdeddaim** I had the great to chance to co-advise with Andrzej Duda (LIG, sept. 2007 - oct. 2009).

3.4.1 Multichannel extension for IEEE 802.15.4

After having studied the interest of multichannel for IEEE 802.11 networks, we concluded obviously this technique would also be appropriate for energy constrained networks. While these networks are designed to relay a small amount of packets, they operate with a very low duty cycle ratio. Thus, these networks always operate close to the saturation point. Indeed, if the network is not enough loaded, this means it should operate with a lower duty cycle ratio. The beacon enabled mode with the cluster-tree topology is required to make the solution energy efficient (cf. chapter 2.1.4).

All the coordinators form a tree and each of them must maintain its active part to exchange packets with its children. The standard mentions the active part of one node and its child must be interspaced by `starttime`. Figure 3.19 represents the possible scheduling of the active parts to avoid efficiently the collisions. In particular, the active parts of A and E are overlapping because these coordinators are not mutually interfering. On the contrary, C and D must choose a different `starttime` to limit the number of collisions.

[Mut+09] proposed MeshMac which schedules the active part after having collected the information in the 2-neighborhood. The authors introduced a new MAC primitive to scan the neighborhood and to ask explicitly the list of neighbors. However, a scan makes the node deaf to other transmissions. [Kou+08] presented a centralized approche to assign the active time for each coordinator. [JK07] proposed to create a dedicated part to `beacons` at the beginning of the active part: several coordinators may share the same active part without their beacons collide. However, the data frames keep on colliding.

Multichannel Cluster-tree

Since such scheduling is complicated to obtain, we proposed a multichannel cluster-tree [NAP12; Abd+12] as illustrated in figure 3.20. Any coordinator with at least one child has to choose both one channel and one active part.

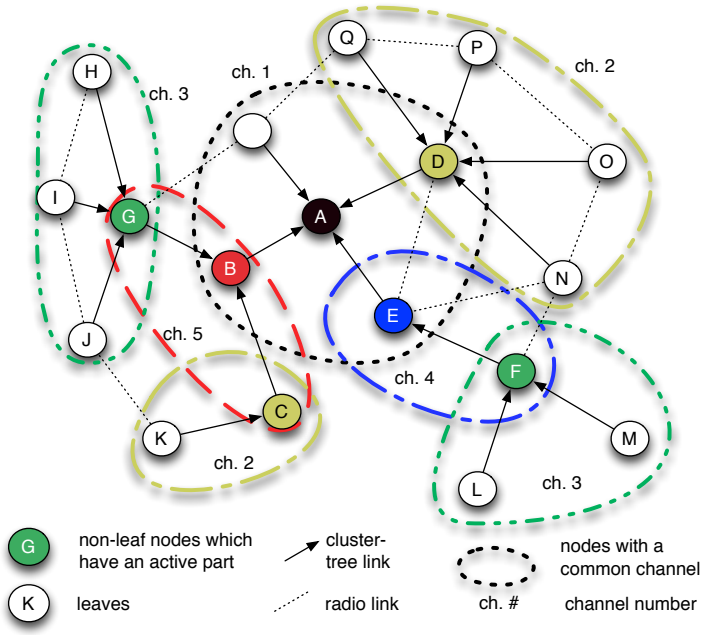


Figure 3.20: Cluster-tree using several channels

Neighborhood discovery and maintenance

Neighborhood discovery in multichannel environment may be very large, particularly when the Superframe Duration is unknown a priori [Kar+13]. For instance, 96 minutes are n average required to discover a coordinator when a coordinator uses BO=14.

We proposed to use a common control channel when a coordinator MUST send an `hello` packet when it is not during its active part or those of its parent. The hello transmission is triggered randomly during the sleeping time, to avoid a repeated collision with a coordinator. An `hello` packet contains:

- ids of neighbors;
- their active part;

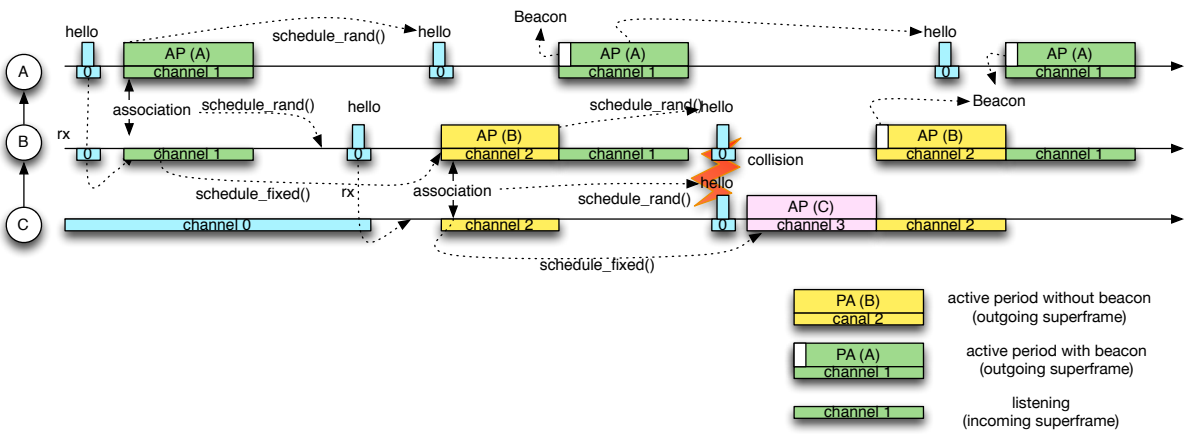


Figure 3.21: Discovery process

- depth;
- the channel they use.

Figure 3.21 illustrates this process. A is the PAN coordinator and sends its `hello` over the control channel. B receives the packet, extracts the offset to know the active part of A. Then, it can engage an association with A over its channel. Finally, it chooses its own channel (2) and starts to transmit its own `hellos` so that for instance C can join the cluster-tree.

Construction

To limit the number of collisions, we minimized the number of coordinators which must maintain an active part. Thus, we have to maximize the number of leaves in the cluster-tree, to create two types of coordinators:

active coordinator: this node has the same role as in the IEEE 802.15.4 standard, transmitting their `beacons` and coordinating their active part;

passive coordinator: while being a Full Function Device, it does not maintain an active part and does not send any `beacon`. However, it authorizes an association by sending periodically some `hello` packets over the control channel. As soon as a passive coordinator has a new associated child, it becomes active and maintains its active part.

Since IEEE 802.15.4-2006 performs poorly when too many nodes contend with each other during an active part, we bound the number of children in the cluster-tree. A node associates preferentially to a coordinator which has between 1 and $MAX_{children}$. If no such coordinator exists, the node selects a coordinator without any child.

While this heuristic is very simple, we verified it performs quite well practically in dense networks. However, it would be logical to propose a more accurate cluster-tree construction algorithm.

Channel and active part assignment

We chose simple heuristics to schedule the active parts: a node places its active part according to its depth in the cluster-tree. We avoid the deafness problem: the active parts of two consecutive nodes in the cluster-tree do not overlap.

We set consequently:

$$tspace = \frac{BO - SO - 1}{k}, k \geq 2 \tag{3.1}$$

Between two `beacons`, we have exactly k active parts.

With the same topology as previously, we would obtain the scheduling described in figure 3.22 (here, $k = 2$). The nodes C and E have no child: they are passive and have no active part. The active coordinators with an even depth use the slot 0 while the other ones use the slot 2.

With such assignment, we can implement a locally adapted duty cycle ratio. Indeed, a branch of the cluster-tree may reduce the sleeping time (SO parameter) without any impact on the other nodes in the tree. We can consequently have different SO values for the different branches: each branch may adapt it duty cycle ratio to actual quantity of traffic it forwards.

Finally, we implemented a greedy channel assignment to each active coordinator to avoid the collisions between coordinators with the same depth.

Performance evaluation

We simulated topologies of 60 nodes with an average degree of 9. We use CBR flows, in convergecast (toward the PAN coordinator, along the cluster-tree) with 1 packet every 2 minutes. By default, SO=1. We compared our solution with MeshMac [Mut+09] assuming the 2-neighborhood is known for free (optimistic scenario for MeshMac). We used the wsnet simulator with a PHY layer calibrated according to the scenario FB6 (indoor deployment) presented in [CT11] (shadowing, path loss= 1.97, standard deviation= 2.0, $Pr(2m) = -61.4dBm$).

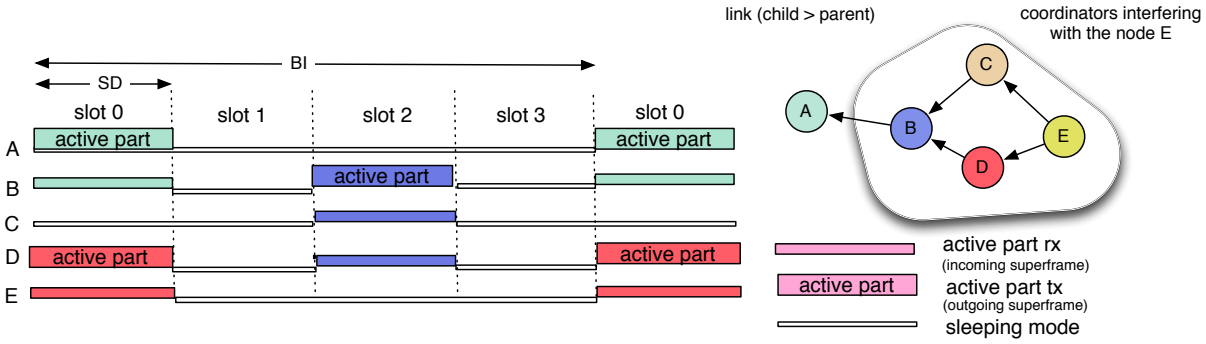
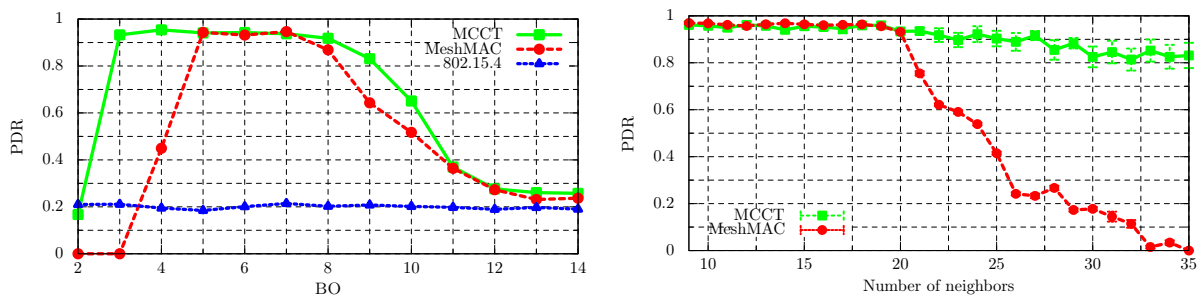


Figure 3.22: Scheduling of multichannel active parts with $k = 2$



(a) Impact of BO

(b) Density

Figure 3.23: Topology of 60 nodes, SO=1

When the beacon interval is large, MeshMac performs quite well: the number of active parts is large (Fig. 3.23a). However, the multichannel version increases the capacity (low BO values). This property is particularly interesting when we aim at optimizing the delay or we want to handle bursts of packets because e.g. the same event is detected simultaneously by a collection of nodes.

When we consider dense topologies (Fig. 3.23b), the multichannel version still performs better. Since many applications target dense deployments (e.g. smart buildings), we think this could constitute an interesting property.

3.4.2 IEEE 802.15.4: self-adaptation

Medium access with IEEE 802.15.4

CSMA-CA was slightly modified compared to IEEE 802.11. The emitter must first wait the end of the current backoff-boundary if it is in beacon-enabled mode. Then, it triggers a random backoff with a value comprised between 0 and 2^{BE}, during which it turns off its radio. When waking up, it triggers two successive CCAs. If the channel is busy, the node must increment the number of retransmissions (NB) and its backoff exponent (BE), and must choose another backoff if the number of retries does not exceed a threshold value. If the medium is free, the packet is transmitted and the node waits for an ack.

This technique is very agressive and leads to poor performance (Figure 3.18).

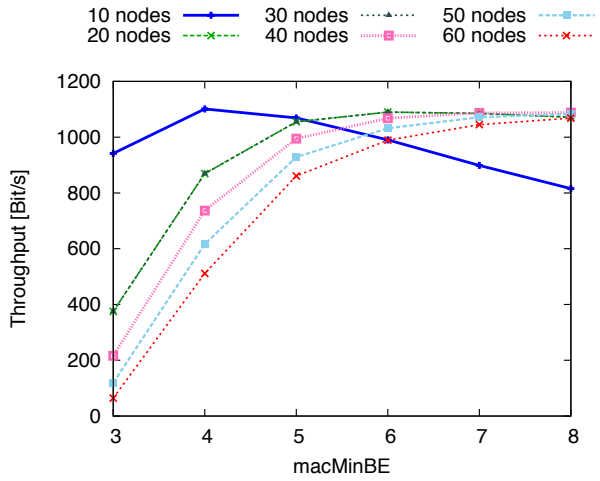


Figure 3.24: Impact of macMinBE on the throughput

Scientific challenge

With the multichannel version of IEEE 802.15.4, we have a collection of independent stars. Could the unreliability problem of IEEE 802.15.4-2006 be solved by choosing simply more accurate parameters values?

We have studied systematically the impact of each parameter on the IEEE 802.15.4-2006 performance [Abd+13]. We lead to the following conclusions:

macMaxCSMABackoffs: maximum number of times the channel is sensed busy before a frame is dropped. This value should be arbitrarily large. Indeed, sensing the channel is very inexpensive, and dropping such frame may under-use the rest of the active part;

macMaxFrameRetries: maximum number of retransmissions without acknowledgment. This parameter has a very low impact for a value larger than 2, as already highlighted by Anastasi et al. [Ana+09]. Only a few frames are dropped because of this event;

Backoff Exponent (BE): a node chooses randomly its backoff between 0 and 2^{BE}, BE being initially fixed to macMinBE and is incremented for each transmission failure (up to `macMaxBE`). Figure 3.24 shows the optimal value greatly depends on the number of nodes, their traffic. We have consequently proposed an heuristic to find dynamically the optimal value.

Self-adapting BE

We first derived an analytical formulation of the collision probability, using mainly the model proposed for idle sense by Heusse et al. [Heu+05]. Although both protocols differ significantly (residual backoff with IEEE 802.11 and the drop after two consecutive CCAs with IEEE 802.15.4-2006), both formulations are surprisingly very similar. Besides, the sleeping mode of the nodes during the backoff have also no impact on the analytical formulation.

By counting the number of idle slots, we can find the optimal value for the Backoff Exponent. The coordinator is the only one which stays awake during the whole active part: it computes the optimal BE value and piggybacks this value in its `beacons`. The nodes will use this new value during the next active part.

Table 3.2: Simulation parameters

Parameter	Value
Aire	100m x 100m
Saturated traffic	always a frame to send
Duration	100000 s
number of nodes	up to 32
Propagation	unit disk graphs
Duty cycle ratio	1%
Frame size	30 bytes

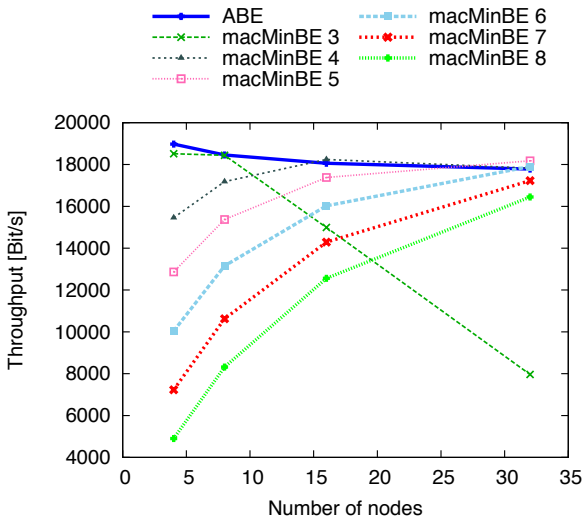


Figure 3.25: Throughput in saturated mode

Traffic may be variable: some active parts may consequently be empty. The coordinator would take an agressive decision by selecting the minimum BE: this would create a burst of collisions during the next active part. We chose rather to send the maximum BE when no traffic is measured. Indeed, contention is reduced, and this would not justify a smaller BE value, which would reduce the transmission delay but would also increase the number of collisions. This conservative approach succeeds to reduce the number of collisions with a fluctuating traffic.

Performance evalaution

We compared our self-adaptive solution (ABE) with the behavior of IEEE 802.15.4-2006 using the fixed value of BE. We used wsnet with the parameters described in table 3.2.

We verified that ABE is able to find the optimal BE value in saturated mode (Figure 3.25), whatever the number of active nodes is. We don't need anymore to manually search for the best value when we have to deploy a WSN using IEEE 802.15.4. This self-adaptation mechanism is a key feature for the Internet of Things.

We also verified that this solution still performs well in non saturated mode, with a Poisson traffic [Abd+13]. In any case, ABE operates always close to the optimal value (±5%).

3.4.3 Limits and Perspectives

We proposed here two improvements to IEEE 802.15.4-2006. In a first time, we proposed a multichannel extension, constructing a cluster-tree with a large number of leaves. We presented also a simple scheduling algorithm of active parts, based on the depth in the cluster-tree. We reduce the number of collisions and simplify the scheduling process. Besides, we also enable a new method to locally adapt the duty cycle

ratio to the actual traffic forwarded by the cluster-tree branch. We authorize the network to react quickly to sudden traffic increase.

In a second time, we also proposed a self-adaptive mechanism for IEEE 802.15.4, reducing the problems of the medium access aggressiveness. In particular, we proposed a simple mechanism to adapt the Backoff Exponent value to the actual traffic conditions, inspired from Idle Sense [Heu+05].

However, we did not solve all the problems of IEEE 802.15.4. While the self-adaptation performs well in star topologies, the multihop transition is more problematic. Indeed, some coordinators have more traffic to forward, because for instance their subtree is very large. We should consequently apply a proportional fairness. However, weighting the backoff according to the subtree size is dangerous: this dynamic value may oscillate. We could use the buffer size, but the coordinator does not know a priori the buffer occupancy for each of its children. Besides, we cannot authorize each child to select the best value by itself: it does not know the load of its siblings. This problem is consequently still open.

Recently, IEEE 802.15.4-2012 has been proposed by the IEEE working group, detailing significant modifications of the previous IEEE 802.15.4-2006 version. It proposes in particular several new modes. The TSCH mode implements a low frequency channel hopping, paired with a TDMA scheme to reduce the number of collisions and to increase the reliability. However, the current implementation leads on a centralized assignment of bandwidth for each link, using a Path Computation Engine (PCE). Such approach is only feasible with a constant and/or predictive traffic.

The DSME mode schedules the active parts of each coordinator as previously. IEEE 802.15.4-2012 authorizes frequency hopping (a *channel offset* is assigned to each coordinator). Our multichannel version of IEEE 802.15.4-2006 should be easily modified to work with DSME. A coordinator would use a *channel offset* rather than a fixed channel. The nodes are already synchronized along the cluster-tree, reducing the clock drifts and the guard times. Besides, it also improves the 2006 version by re-organizing the GTS. With the CAP reduction technique, the CAP is only present in the first superframe, while the other ones contain only GTS. Besides, a GTS may be reserved for any pair of nodes, i.e. the communications don't pass all through the coordinator. The adaption of the multichannel GTS to our solution seems more complicated. Using channels dedicated to GTS could be possible, but would waste the radio bandwidth.

3.5 Conclusion

We presented here how multichannel may solve some of the problems created by the MAC layer in multihop topologies. We reduce the number of collisions and improve the fairness, key performance metrics in multihop. When using a multiradio node, channel switching seems useless: the bandwidth is only slightly improved, counterbalanced by the overhead and the complexity. However, to handle the contention efficiency among interfering nodes remains an open problem, as we highlighted in the simulations with IEEE 802.11s. The collisions between data and control frames are in particular very prejudicial to the network operation.

In single interface networks, we proposed Molecular MAC, organizing the transmissions inside a molecule: some nodes are static while the other one change dynamically the channel they use. The molecule organization removes any deafness problem and increases the network capacity. Besides, no synchronization is required, contrary to most of the solutions in the literature. However, a routing protocol exploiting this molecule has still to be proposed.

When we take into account the energy consumption, multichannel mays also be interesting to reduce the scheduling complexity of active parts. Besides, we proposed some self-adaptation mechanisms to the protocol so that it always operate with the optimal parameter values. We remove now any manual tuning. We significantly improve the throughput of IEEE 802.15.4-2006, which performs very poorly even in a star topology.

For all these MAC layers, we still have to propose efficient routing protocols. Indeed, the particular characteristics of these MAC layers should be exploited efficiently by the routing layer. For instance, the cluster-tree is not redundant: load balancing and reliability may be difficult to achieve. We will explore this problem in the next chapter.

3.6 Related Publications

Conferences

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[Oli+12] Carina Teixeira de Oliveira, Fabrice Theoleyre, and Andrzej Duda. "Channel Assignment Strategies for Optimal Network Capacity of IEEE 802.11s". In: *International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN)*. ACM. Paphos, Cyprus, 2012.

[The+09b] Fabrice Theoleyre, Benoit Darties, and Andrzej Duda. "Assignment of Roles and Channels for a Multichannel MAC in Wireless Mesh Networks". In: *International Conference on Computer Communications and Networks (ICCCN)*. IEEE. San Francisco, USA, 2009.

Chapter 4

How could we route packets efficiently in multihop networks?

In the previous chapters, I mainly focused on resource sharing in the MAC layer. We limit the problems created by hidden, exposed and blocked terminals. However, how could we create efficient routes to exploit this meshed topology?

I am convinced routing and MAC cannot be designed independently from each other. Indeed, the radio link quality is intimately related with its exploitation by the MAC layer. A routing protocol should take into account the fact that a radio link may be handled properly by the MAC (e.g. intra and inter-flow interference, load). In the same way, the topology control solutions in the MAC layer reduce the routing choice.

In this chapter, we tried to study finely these interactions, and to propose adapted routing protocols. I will here focus mainly on **energy constrained wireless sensor networks**, since I was not able to study sufficiently the routing problem associated to the IEEE 802.11 multihop networks.

We propose to study here transversally how we may exploit efficiently a multihop wireless network:

1. in a first time, we will explain how *geographic* routing reduces the quantity of information to save in each node, while surrounding the local disparities in the network topology (often designated *voids*);

2. several experimental studies have highlighted the instability of WSN, and the complexity to estimate the link quality of the routes [Ren+11; Cer+05b]. We tried to analyze the measures obtained by Orange Labs on their testbed to characterize this environment;

3. in wireless sensor networks, the topology control in the MAC layer (e.g the cluster-tree of IEEE 802.15.4-2006) may create conflicts with the routes created by the routing protocol (RPL with a DAG). How could we modify this control to make the cohabitation more efficient?

4. RPL constructs a Directed Acyclic Graph (DAG), rooted at the border routers (gateway to the Internet). We have studied the properties of this structure, in particular the impact of the metric on its stability.

4.1 Related Work on Routing

Routing in multihop wireless networks has already been widely studied. The reactive family aims at creating routes *on-demand*, when a node has packets to transmit. On the contrary, the proactive family creates routes *a priori*, ready to be used. A huge number of routing protocols have already been proposed in sensor, ad hoc, and mesh networks to deal with a set of specific constraints [AY05; AM12].

4.1.1 Wireless Sensor Networks

A routing protocol for such networks should maximize energy savings and improve the network lifetime. Indeed, a packet forwarded in multihop should minimize the energy spent by relays (number of hops, retransmissions). Besides, it must also balance the load so that each node has the same amount of energy to consume.

The IETF ROLL (Routing over Low-Power Lossy Networks) working group has explored how IP routing may be adapted for Wireless Sensor Networks. 6LoWPAN [6Lo] proposes compression techniques to use IPv6 addresses. Winter [Win12] describes the RPL routing protocol. RPL creates a Directed Acyclic Graph rooted at the border router. This structure is particularly well suited for a convergecast traffic pattern when all the nodes must send their measures to a processing unit present in the Internet. Sending data to the nodes is possibles, but the diffusion of control packets is more expensive.

Because they highlighted some key problems when deploying RPL experimentally [Cla+13a], and arguing that the creation of routing loops may make the environment unstable, another working group proposed LOADng [Cla+13b]. However, this reactive approach, to my point of view, has difficulties to explore and estimate accurately the radio link quality. Besides, LOADng may have difficulties to detect asymmetrical links.

4.1.2 Routing metrics

Using shortest paths performs badly in wireless sensor networks since such protocol tends to use the worst radio links [Par+09]. Consequently, several metrics have been proposed to take into account the throughput, the reliability or the energy efficiency. ETX initially proposed to maximize the throughput by estimating the packet delivery ratio [DC+03]. As edge effect, ETX also estimates indirectly the energy efficiency in WSN: the metric estimates the number of retransmissions. Several variants have been proposed. In particular, Sang et al. [San+10a] estimates finely ETX for asymmetrical links.

Recently, Liu et al. [Liu+12] proved a metric based on the delay creates instabilities in experimental conditions. They proposed a multi-scale temporal estimation to improve the accuracy. However, interference estimation and load balancing are also important, and are seldom integrated in the routing metric. A routing metric should both capture the path quality and avoid oscillations ([Liu+09; Cam+08]).

4.1.3 Experiments

Several platforms have been deployed to evaluate experimentally the wireless sensor networks [Sen08; Fit; Ras+07; Sen; Aqu07; TWI12]: the protocols are evaluated *in vivo* to understand more finely their limits. These experimental studies highlighted several phenomenon which could greatly impact the performance of such network. Liu et al. [Liu+09] and Campista et al. [Cam+08] proved oscillations may arise in the routing protocol. A recent study on RPL [GK12b] noticed oscillations when the protocol uses the ETX metric.

Recently, Liu et al. [Liu+11] emphasized the WSN are not scalable: packets are dropped when the network becomes too large. In the same way, Clausen et al. [Cla+11] highlighted packet drops are very frequent practically and generate a large number of control packets.

Cerpa et al. [Cer+05b] have presented a pioneering piece of work to characterize the radio link instability, and its impact on the routing process.

These experimental conclusions are not limited to WSN. Raman et al. [Ram+09] aimed in particular at validating the concept of *radio link abstraction* in multihop rural Wifi. In other words, could we consider the radio link characteristics are stable over time? Contrary to campus networks, the authors concluded rural mesh networks present stable links. However, in urban environments, the radio link exhibits a much more instable property, because of extern or intern interference.

We still now have to design a stable and efficient routing protocol. Such standard should guarantee probabilistically some performance metrics, even using an unreliable network.

4.2 Geographic routing or the art of bypassing voids

If each node has a geographic location information, we can reduce the routing complexity by using a *geographic* approach [Bos+99; CE07; He+06; Cas+07]. When a node receives a packet to forward, it applies the following rule:

"select the neighbor which has the largest improvement toward the destination".

The *improvement* is often defined as the difference in euclidean distance with the destination. If we forbid a packet to go farther from the destination (negative improvement), we avoid any routing loop.

However, such protocol exhibits a major problem in non perfectly homogeneous topologies, in particular with *voids*: no neighbor exists with a positive improvement. The node must in this case drop the packet.

The *face-routing* approach proposes to apply the left hand rule [KK00]. After having planarized the graph, the neighbor immediately on the left in the direction of the destination is selected. However, a network is not in general planarizable [Kim+06].

A node may also initiate a local flooding to discover a relay node [Sto+01]. Fotopoulou-Prigipa and McDonald [FPM04] adapted this approach to create and maintain a *virtual circuit* to make the route durable. Funke [Fun05] proposed to construct isosets to bypass voids. However, in non UDG, the isosets may not be rings, which creates new problems.

Scientific challenge

How could we use geographic routing while bypassing efficiently the voids, whatever the topology is (UDG or not)?

While the geographic routing protocol presented here is independent on the MAC layer, focus of this manuscript, I chose even to present this work. Indeed, this study lead myself to think about layer independency of the different layer.

This work was done with **Eryk Schiller** when he was a Ph.D. student advised by Andrzej Duda (LIG).

4.2.1 Geographic routing in random topologies

We first studied analytically the topology we may obtain when the nodes are uniformly and randomly distributed [Sch+07].

In particular, we formulated the average number of neighbors existing for one node, and the probability the greedy rule does not give any next hop. We emphasized the probability of packet loss may be modeled with a Fermi-Dirac function. In particular, the probability of loss due to a void does not follow a percolation model when the density increases.

4.2.2 Reactive deviation

We don't assume anything on the connectivity graph. Since the main drawback of the greedy geographic routing protocol resides in the voids, we proposed to deviate the packets around the blocked nodes (i.e. without neighbor in the direction of the destination).

We detect reactively the blocked nodes [The+09c; The+09a]. Consequently, no control traffic is generated when no data packet is transmitted. A node becomes *blocked* when it receives a packet to a destination for which it has no possible next hop.

Our approach *deviates* the packets. We detect the voids and propagate locally their existence so that all the nodes around the void are able to deviate their packets. As soon as a node is blocked, it sends

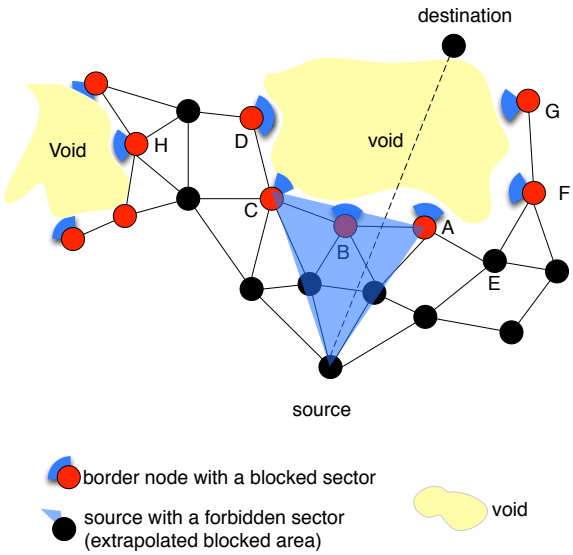


Figure 4.1: Détection locale des limites d'un trou

back the packet to its previous hop and piggybacks the list of its blocked directions. Each node is then able to aggregate this information and to detect the *contours* of the void, deviating the packets out of the blocked cone. The contour is extrapolated as the sector embracing the connected set of blocked nodes.

Performance evaluation

We focus here on the simulations results obtained with ns2. We simulated 10 flows of 4 pps, with packets of 512 bytes. We used the two ray ground reflection model. We measured the ratio of packets dropped because no next hop exists (figure 4.2). We can verify that our rules improve the packet delivery ratio, solving some of the problems of the greedy rule.

4.2.3 Limits and Perspectives

We have here studied how we may modify the geographic routing rule to maintain the greedy progression in most cases and to switch to a reactive mode when a void is detected. Each node is able to construct the sector comprising the blocked destination. By collecting the information in its k-neighborhood, a node is able to extrapolate the blocked relays, computing a forbidden sector to deviate the packets.

However, this is a *best-effort* method, without delivery guarantee. This seems for us a severe limit: a pair of nodes may be unable to communicate if some intermediary nodes extrapolate *too much* the blocked sectors.

Besides, we consider that these rules are triggered in a reactive manner. Thus, we assume implicitly the voids are an exception. This routing scheme does work only in very dense topologies, sufficiently uniform (urban environments, without obstacles).

Finally, we did not discuss here with **the problems specific to radio links**. Greedy geographic routing minimizes the amount of information to maintain. However, it is inaccurate to select the neighbors with the best links. We may execute a neighborhood discovery, test the quality of each link. However, we would not have anymore a memory-less routing protocol.

This memory-less approach is difficulty applicable to wireless sensor networks: a node must be aware of the sleeping schedule of its neighbors. This knowledge breaks the memory-less property of the routing protocol.

After this study, I am convinced that geographic routing is not the accurate solution for multihop wireless networks, where the radio link *quality* is primordial. Besides, some nodes constitute key desti-

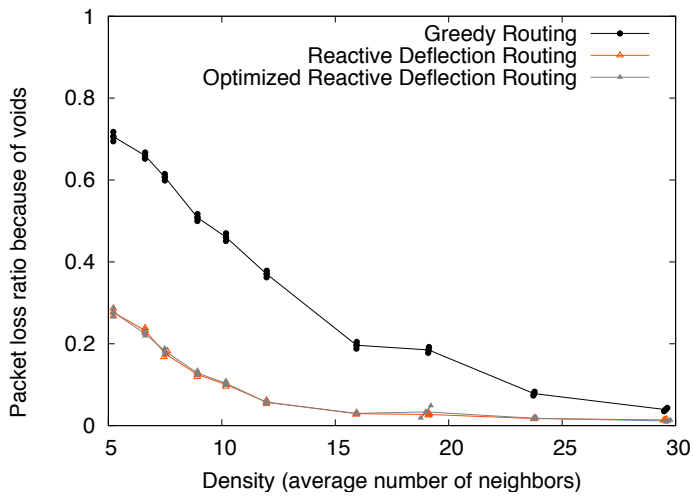


Figure 4.2: Packet losses because of voids with ns2 (i.e. no next hop)

nations in the network (particularly in WSN). Thus, proactive approaches seem more accurate to deal with this situation for congestion avoidance.

4.3 Experiments: characterizing the radio environment

Many protocols have been proposed in wireless networks to solve the routing problem. Designed *in vitro*, they perform often very poorly experimentally, emphasizing several limits. For wireless sensor networks, Barrenetxea et al. [Bar+08] advocated a pragmatic design, *as simple as possible*. However, the scalability of such solution is very limited.

Many platforms have been set-up by the research community for the experimental evaluation. Orbit-Labs was a a percursor, deploying a grid of IEEE 802.11 nodes [Ras+07]. Other researchers tried to control more finely the experimental setup to improve the reproducibility, such as [Fly+02; KR01; San+03].

Raman et al. [Ram+09] presented a pioneering piece of work in the experimental research. They demonstrated that the instability in IEEE 802.11 networks was mainly due to extern interference. It is not related to the intrinsic characteristics of the radio link itself.

Scientific challenge

We aimed here at exploiting the experimental results obtained in the measurement campaign obtained through the SensOrLab [Sen13] testbed, deployed by Orange Labs at Meylan. From these measures, could we characterize finely the radio link quality? its predictability?

This work is fully part of the Ph.D. thesis of **Bogdan Pavkovic** I had the great chance to co-advise with Andrzej Duda (LIG, nov. 2009 - Dec. 2012).

4.3.1 Experimental description

The platform is composed of 36 Coronis nodes, implementing the Wavenis technology [Wav]: fast frequency hopping to be robust to narrow band noise. The MAC layer follows a CSMA-CA approach.

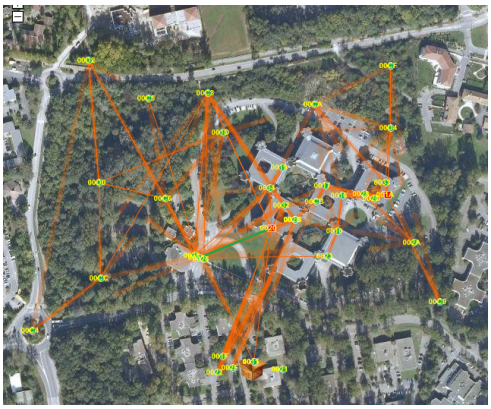


Figure 4.3: Topology of the sensorlab testbed — Orange Labs Meylan

Besides, 2 nodes collect the traffic and act as sinks. We analyze the results Orange Labs obtained during a campaign of 18 days (Figure 4.3) [Pav+10].

The testbed was initially designed to validate a routing protocol [Wat+09]. Each node maintains its virtual distance to the sink, and the next hop is opportunistically selected among the neighbors closer to the sink (smallest virtual distance).

The nodes execute a neighborhood discovery every 13 minutes to maintain a neighborhood table, including the RSSI for each neighbor and its virtual distance to the sink. Each node generates a packet every 17 minutes, transmitted in anycast to the sink. The packets include the neighborhood table of the source. Are also inserted some control information (source, destination, sequence number, etc.)

Main results

We analyzed statistically the experimental results obtained with SensOrLab [Sen13]. We studied in particular:

bidirectional versus unidirectional links: most of the links report a RSSI value in both directions. The asymmetry may come from e.g. non perfect omnidirectional antennas [Sco+06], non homogeneous bandpass filters [LL08] or heterogeneous transmission powers [San+10b].

RSSI characterization: the RSSI measured in both directions for each radio link is relatively symmetrical. However, we were not able to determine the distribution of measures: they do not follow neither a normal distribution (Shapiro-Wilk test) nor a Cauchy or Logistic distribution (Kolmogorov-Smirnov test);

link existence duration versus RSSI: we measures the ratio of hello packets received in both directions. The correlation with the RSSI is low. Good radio links have mostly an high RSSI ($> -75dBm$) or a medium RSSI with a short geographic distance.

dynamics: the neighborhood table changes significantly, with unfrequent stable periods. Proactive solutions choose a next hop for a long time. Thus, this observation tends to privilege the opportunistic solutions: a set of nodes is selected to relay the packets, and the actual next hop is selected during the transmission.

4.3.2 Limits and Perspectives

We studied here the RSSI value of different radio link obtained through an outdoor urban platform (SensOrLab [Sen13]). In particular, the RSSI value does not permit to predict accurately the radio link quality (we noted the cumulative link duration). Besides, we verified the dynamics of such network is high, justifying the opportunistic routing solutions, to make the transmissions more reliable.

However, this platform was originally designed to validate a routing protocol. Since the measures were piggybacked in the data packets, we don't have any measure when the data packet is lost. Besides, the intervals of measures are quite large (17 minutes): we cannot capture the short variations.

Finally, interference cannot be estimated with this experimental setup. However, interference may have a strong impact on the performance. Extern interference may for instance create asymmetric links (the nodes closest to the interfering source may be deaf to the other transmission). Interference creates an asymmetrical view of the medium activity, as exposed in the chapter 1.2.1, with a negative impact on the fairness and throughput.

There still remains some important work to do here to more accurately understand the experimental conditions. We should have more accurate models to understand the key phenomena which impact the multihop wireless network. The recent standard – IEEE 802.15.4e-TSCH – assumes that frequency hopping makes the radio link stable: is that true in any environment? How could we deal with very dense topologies of co-located networks using possible different technologies? In the same way, wouldn't several co-located IEEE 802.15.4e-TSCH networks create collisions if the Internet of Things grows very quickly?

4.4 RPL fundamentals

We will now focus on the RPL routing protocol [Win12]. We propose consequently to detail here some of its key features.

RPL is a distance vector routing protocol, initially designed for topologies of thousands of nodes. The protocol constructs a simple routing structure, by limiting the number of packets to maintain the routes. RPL focuses mostly on the convergecast traffic pattern, where all the packets are generated toward the sink (called border router in RPL).

Optionally, a node may also be a destination. However, it must be registered in the border router and must refresh periodically its route with control packets (`DAO`) forwarded along the tree to the sink. This process is expensive and supports only a small number of such flows.

RPL is based on a *Destination Oriented Directed Acyclic Graph (DODAG)*, rooted at the border router. Each node maintains a virtual distance to the sink. A node may select as parent (kind of next hop) all the nodes with a smaller virtual distance. Consequently, RPL avoids the creation of loops.

4.4.1 DODAG construction

RPL uses the notion of *rank* to construct the DODAG. A rank denotes its virtual distance to the sink (the border router). To avoid the loop creation, the rank must monotonically increase in the DODAG from the root to the leaves.

The *objective function* is in charge of computing the rank by combining a set of metrics. For instance, the OF0 function [Thu12] is the only one required by the rfc: the rank of a node is thus of its preferred parent incremented by a certain value. This increment may integrate administrative constraints (link or parent type) and the link/node quality. For instance, a quality may be associated to a radio link, and the rank represents finally the sum of the quality for all the links constituting the path to the border router.

The border router starts to send periodically a DODAG Information Object (DIO) including among others its rank, the objective function, and the DODAG id. Each node listens to the DIO and saves them to join later the DODAG. Finally, it selects as preferred parent the node which would give it the smallest rank [Thu12].

A node then inserts in the list of its parents all the neighbors which have emitted a smaller rank than itself. However, only the preferred parent is actually used to route packets. Finally, we can note that a node does now know a priori the list of its children – i.e. nodes having chosen it as preferred parent.

Let consider the topology created by RPL in figure 4.4. E aims at joining the DODAG and has two choices: B would give a rank of 5 (3+2) while A would result in a rank of 6 (2+4) since it has a bad radio link. E will select B as preferred parent. However, it will maintain A in the list of its (backup) parents since it has a smaller rank than itself ($2 < 5$).

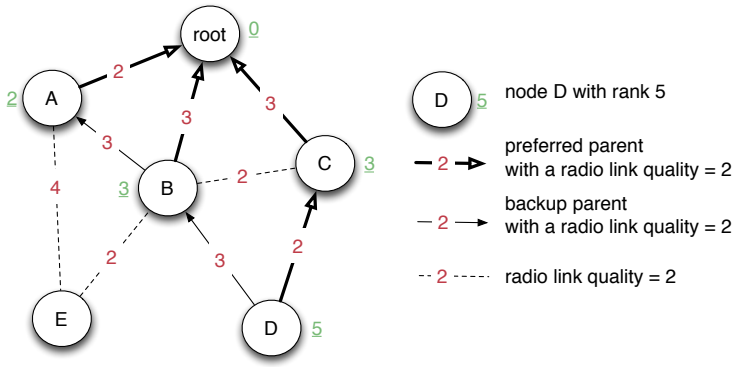


Figure 4.4: DODAG topology used y RPL

4.4.2 Trickle algorithm

Even when RPL has converged, the protocol keeps on transmitting periodically DIO to maintain the DODAG. However, DIO consume bandwidth and energy. Trickle proposes to adapt the DIO period: the stabler the network is, the larger the DIO period is [Lev+rc].

When a node receives a DIO with consistent information (no difference with the previous DIO), it doubles the DIO period. On the contrary, when an inconsistency is detected (its preferred parent has for instance changed its rank), the node resets its DIO period to its minimum value. This reset is very agressive and increases the control traffic. However, it also accelerates the convergence.

4.4.3 Routing metrics for lossy links

Tripathi et al. [Tri+12] highlighted the *wave* behavior of trickle: the routing topology is never stable, reseting regularly the trickle timer. Tripathi et al. [Tri+12] proposed to trigger a parent change only when the metric becomes sub-optimal ($> 30\%$). However, this threshold would represent a very large cumulative difference, and is fixed currently to an arbitrary value. It would be preferable to solve this instability problem by understanding it more finely.

Recently, Gaddour and Koubâa [GK12a] have emphasized that he quality is strongly degraded for nodes far from the DODAG root when the ETX metric is used. Consequently, farther nodes suffer from packet losses because the routes are longer and suffer also more from the instability problem: ETX seems have difficulties to capture efficiently the radio link quality.

Finally, Liu and Feng [LF09] have studied the impact of several metrics on a convergecast tree (Collection Tree Protocol). They isolated a larger instability for ETX.

4.5 Should MAC and routing layers be considered independently?

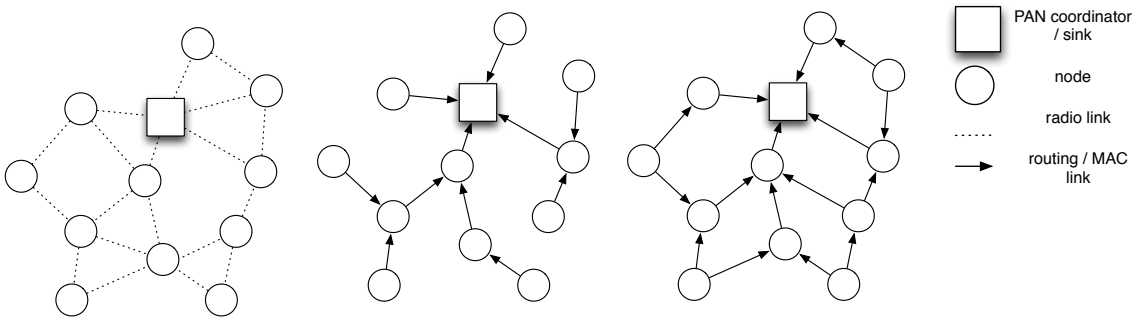
The research community has focused in the last years on proposing efficient standards to the new Internet of Things, considered a prerequisite for an industrial adoption. The stack comprises the following standards:

IEEE 802.15.4: for the medium access, where the nodes may sleep to save energy [802c];

RPL: to construct routes in low-power lossy networks [Win12];

6LoWPAN: implements IPv6 for small embedded and very constrained devices [6Lo]. They propose in particular header compression since the IPv6 addresses may be very long in small IP packets;

CoAP: translated HTTP requests to support low-power devices [She13].



(a) radio topology (b) cluster-tree (IEEE 802.15.4) (c) ideal DODAG (RPL above the radio topology)

Figure 4.5: Topology control in a IEEE 802.15.4/ RPL network

Traditionally, the IETF vision consists in designing protocols by respecting the layer independency. This structure represents the strength of the Internet: a protocol may be replaced without impacting the other ones.

However, WSN are very constrained in energy, and must operate efficiently in lossy environments. Thus, the cross-layer problem was widely studied in multihop wireless networks [Ian+07; Ruz+08; DF+11; Cuo+13; Bor+06].

Scientific challenge

In a standardized stack, should the protocols be considered separately to be evolutive or this cost is too high to be tolerated?

This work represents the second part of the Ph.D. thesis of **Bogdan Pavkovic** I had the great chance to co-advise with Andrzej Duda (LIG, nov. 2009 - Dec. 2012).

4.5.1 DAG structure for MAC and routing

RPL exploits a directed acyclic graph structure to route packets. Since we aim at minimizing the energy consumption, the IEEE 802.15.4-2006 MAC layer is organized into a cluster-tree.

In figure 4.5c, RPL should be executed directly above the radio topology and could use a redundant routing structure. However, it must practically be executed above the cluster-tree created by IEEE 802.15.4-2006 to save energy. Thus, RPL has no choice in its preferred parent: it must choose the one selected by the MAC layer. Both topology control solutions behave here in an antagonist way.

We proposed consequently to slightly modify IEEE 802.15.4 so that it supports a redundant structure – denoted a *cluster-DAG* – well adapted for RPL [Pav+13; Pav+12].

Multi-parent association

A node should associate with several parents without creating a loop. We aim at constructing a cluster-DAG with a kind of depth, similar to the *rank* of RPL. The depth denotes the virtual distance from one coordinator to the PAN coordinator.

A node collects the `beacons` transmitted by its neighbors, and associates with the coordinator which presents the smallest depth. More precisely, a node computes its depth in the same way as RPL. It selects the parent which minimizes its own depth.

For each new `beacon` received from a node P, a node N applies the following rules:

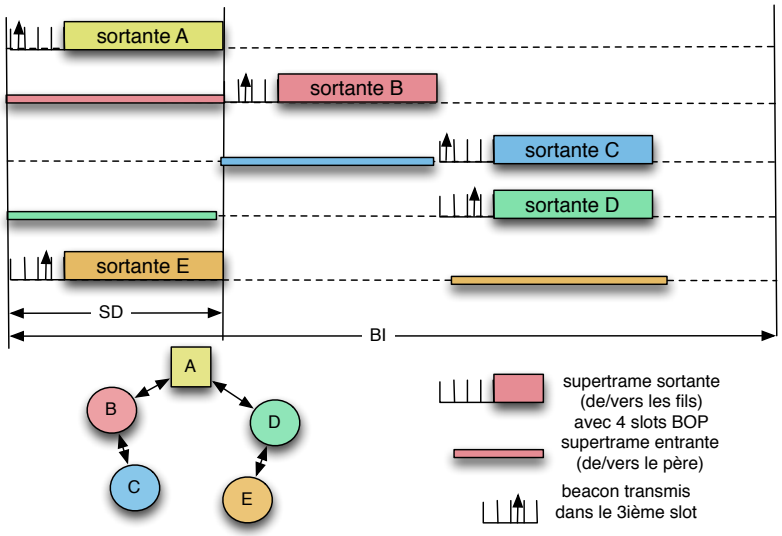


Figure 4.6: Combining a scheduling of both active parts and beacons

depth based selection: P is inserted in the *on-going* parents if it annonces a depth strictly less to the depth of N would have using its best parent. N engages in this case an association with P, and inserts it in the list of its on-going associations. P is definitively inserted into the list of parents when the association is validated (reception of an `association-reply`).

loop removal: if P is already parent, and its depth is is greater than or equal to the depth of N, N must dissociates from P, which became sub-optimal.

We consider here only the already associated parents: an on-going association may fail for instance with an asymmetrical link. We avoid in this way to create convergence problems in the cluster-DAG.

Besides, we forbid the usage of an on-going dissociated parent to avoir routing loops.

A coordinator includes in its `beacons` the minimum value of its depth, considering all its associated parents.

Energy Efficiency

With IEEE 802.15.4-2006, a node consumes most of its energy as coordinator: it must stay awake during the active part of its superframe (e.g. 61.44 ms for $SO = 2$).

A node which follows several parents must wake-up to receive one `beacon` from each of them. A guard time is required to deal with clock drifts. A typical clock drift corresponds to 10 μs per second [Nef+12] (10 ppm), and a `beacon` lasts for 100 μs. In conclusion, a new parent may increase the energy consumption by approximatively 0,18%: this seems negligible.

Scheduling the active parts

Two major techniques exist to limit the number of collisions with IEEE 802.15.4-2006:

1. scheduling the active parts with a TDMA approach, using **superframe slots**;
2. scheduling the `beacons` in a Beacon Only Period (BOP), before the Contention Access Period (CAP) of IEEE 802.15.4, denoted **bop slots**.

Both techniques seem complementary. We have chosen consequently to combine them with the following properties:

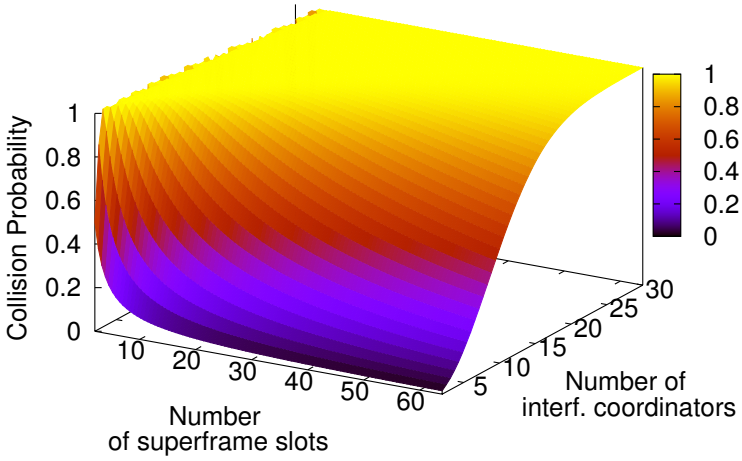


Figure 4.7: Impact of the number of active parts (superframe slots) on the collision probability

- during an active part, only one coordinator with children should be active. We avoid the collisions between the data frames.

  For instance, the coordinators C and D are active simultaneously (they share the same *outgoing superframe*) because C does not have any child.

- when the coordinators interfere with each other and share the same active part, their `beacons` should be scheduled sequentially.

  The `beacons` of C and D are scheduled in two different BOP slots.

Random assignment Let n_{coord} be the number of mutually interfering coordinators and let $n_{sf-slot}$ be the number of possible active parts scheduled without overlap (i.e. the *superframe slots*). If we assign randomly the active parts, we may determine the probability two of them collide (birthday paradox). Since the number of interfering coordinators may increase with the density, collisions will quickly appear if (BO-SO) is small (Fig. 4.7).

We proposed consequently a greedy assignment of both the active parts and `beacons`:

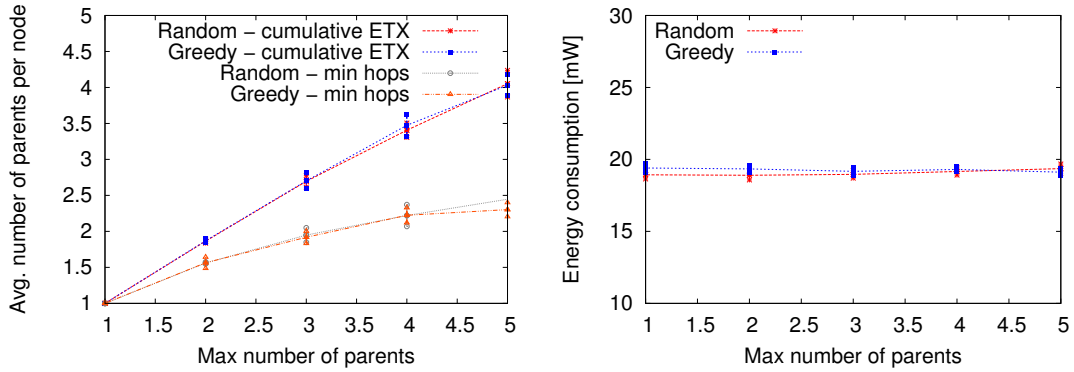
- a coordinator sends periodically an `hello` which includes the list of slots used by its neighbors (both superframe and BOP slots).

- a coordinator reconstructs the scheduling of its 2-neighborhood, and counts the number of coordinator per slot.

- it selects greedily a slot by choosing (with a decreasing priority):

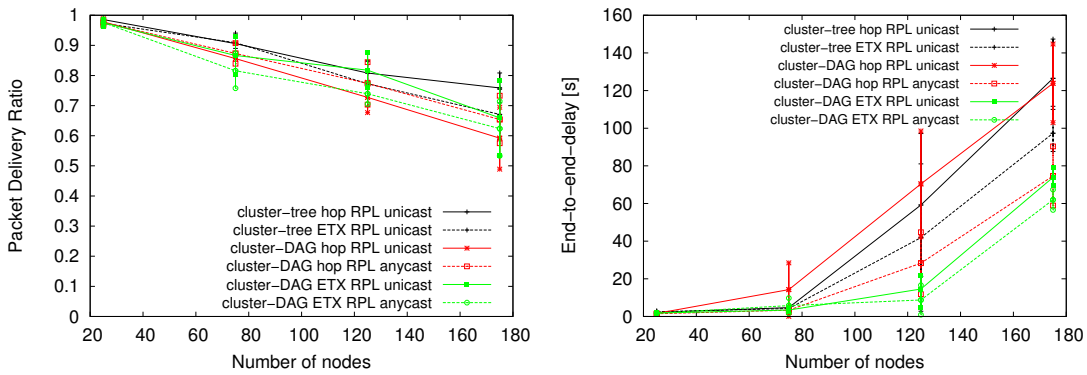
  1. an empty superframe slot;
  2. a superframe slot which contains the minimal number of coordinators with children;
  3. one unused `beacon`.

  If possible, it maintains the same slots has selected previously to avoid unnecessary changes.



(a) Average number of parents per node (b) Energy Consumption

Figure 4.8: Impact of the number of parents on performance



(a) Packet delivery (b) End to end delay

Figure 4.9: Performance of a cluster-DAG/tree with RPL

Performance evaluation We have first studied the behavior of this algorithm, constructing a cluster-DAG with wsnet using the same propagation model as previously [CT11]. We compared the behavior of the construction when ETX and MinHop (shortest hops) are used, regardless of the maximum number of parents. MinHop minimizes the hop count and does not create a sufficiently redundant topology (fig. 4.8a). On the contrary, ETX succeeds to construct a cluster-DAG, really meshed.

We also measured the energy consumption (using the energy consumption data of the CC2420 chipset). We can verify that following several parents presents an acceptable overhead in energy (fig. 4.8b). Practically, most of the energy is consumed during the active period, as coordinator: a child may sleep as soon as its buffer is empty and no notification is sent by the parent.

Then, we studied the behavior of RPL above this topology. We evaluated two transmission modes in the MAC layer:

unicast: only the preferred parent is used;

anycast: the packet is transmitted in anycast to the first parent. This opportunistic approach maximizes the throughput and handles more efficiently the `beacons` losses.

We have first measured the end to end delay (fig. 4.9b) and the packet delivery ratio (fig. 4.9a). An anycast strategy coupled with a cluster-DAG efficiently reduces the end to end delay. However, it reduces slightly the packet delivery: more packets are transmitted to weak neighbors.

Finally, we measured the efficiency of the MAC layer by reporting the number of transmitted packets per packet received by the sink (fig. 4.10). We take into account the number of control packets and of

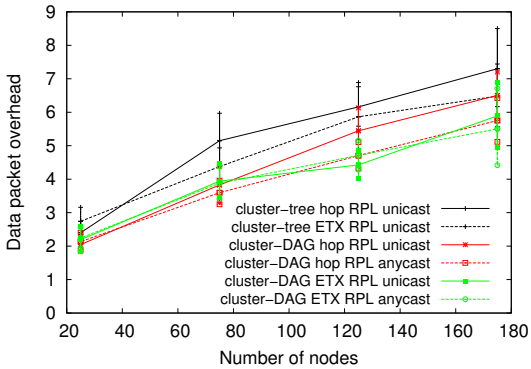


Figure 4.10: Number of transmitted packet per packet received by the sink

retransmissions. We can verify that the cluster-DAG reduces the number of packets required to deliver a packet to the sink.

4.5.2 Multi-criteria routing

We presented in [Pav+11] a routing variant exploiting a cluster-DAG. By following several parents, we are able to implement a differentiated treatment, even with a single DODAG. We may for instance implement a strategy, which takes into account a time constraint: a deadline is associated with each data packet.

When a packet has to be relayed, a node proceeds in the following way:

1. it divides the remaining time before the deadline by the number of hops toward the PAN coordinator. This time budget should be respected for the next hop;
2. When a `beacon` is received:
   (a) it computes the average time before the reception, for each of its parents. It takes into account the time before the next wake-up, the probability to receive the `beacon`, the average number of retransmissions, and is current buffer size;
   (b) It deduces the set of parents respecting the delay constraint: the time before a correct reception must be less to the time budget;
   (c) among these parents, it selects the best one concerning the energy consumption (using for instance the cumulative ETX metric). If the best parent is those having transmitted the last `beacon`, the node sends the packet in the current active part.
   (d) else, it sleeps until the next `beacon` from another parent.

The buffer should be ranked among an increasing deadline. Such algorithm works because all the packets are for the PAN coordinator. Else, we must maintain one buffer per destination, and the routing decision may be more complicated to implement.

We have emphasized by simulations that this modified version of RPL permits to implement a deadline-aware strategy.

4.5.3 broadcast with IEEE 802.15.4

This work represents one of the chapters of the Ph.D. thesis of **Oana Iova** I have the great chance to co-advise with Thomas Noel (ICube, sept. 2011 - *).

While broadcast is widely used in WSN, only a few papers studied how we may implement efficiently such primitive. In particular, IEEE 802.15.4 does not propose such a feature. A child may sleep at any time, and the indirect mode is required to transmit packets from the coordinator. Thus, a node may have

to duplicate a broadcast packet, to send one unicast copy for each of its children. The number of control packets increases accordingly.

Recently, we proposed to modify IEEE 802.15.4-2006 to include sequence numbers, dedicated to broadcast and multicast [Iov+14a]. A node announces in a compact form the list of pending packets, and the associated multicast addresses. In this way, we guarantee a reliable delivery of multicast packets. The `beacons` include this information, and a child has to stay awake if it did not have received one packet: we exploit the broadcast nature of radio transmissions. Multicast packets are not acknowledged but any child may verify it has received all the buffered multicast packets.

We have also proposed multicast addresses to maintain in the buffer one unique packet for a given multicast address. Thus, a new packet replaces the previous one. For instance, a DIO makes the previous one obsolete.

4.5.4 Limits and Perspectives

We presented here a topology control solution where RPL can fully exploit the IEEE 802.15.4-2006 MAC layer. We propose to construct a fully meshed topology, so that RPL can select the most accurate route concerning its criteria. Instead of breaking the layered architecture, we rather proposed to enhance the IEEE 802.15.4 protocol to deal with the specific routing constraints of RPL.

We proposed an extension so that RPL can use several parents (and not anymore only the preferred parent). By selecting opportunistically the next hop for each packet, we minimize one metric (energy consumption) while respecting a constraint (deadline). However, our approach is here only an heuristic: optimizing both the energy and the deadline is impossible with a single DODAG. For an optimal version, we would have to construct one DODAG based on the energy metric for each possible deadline value. Multiplying the number of DODAG would negatively impact the overhead.

The metric used to select the *best links* should be the same in the MAC and routing layers. However, it may be complicated to integrate in the MAC layer some routing decisions. For instance, to balance the load, the routing choice may also impact the link quality: a route selected by many flows will decrease in quality (because of congestion and collisions). However, this routing decision must absolutely avoid oscillations. Indeed, a dynamic DODAG creates several problems in RPL, as we will study in the next section.

4.6 RPL: instability and solutions

RPL [Win12] proposes for routing to exploit a Destination Oriented Directed Acyclic Graph (DODAG), based on the notion of *rank*, kind of *virtual distance to the root* (cf. section 4.4.1). The protocol constructs one DODAG per sink (also called *border router* in RPL).

RPL proposes two types of metrics to construct the DODAG:

node oriented: residual energy, hop count, node characteristics;

link oriented: throughput, latency, reliability, residual energy.

However, only a few papers studied the impact of the metric on the RPL behavior. In particular, does the protocol construct stable routes? The *trickle timer* mechanism has been proposed to reduce the control traffic: when no change is detected by a node, it doubles the DIO period. On the contrary, an inconsistency automatically triggers a reset of the DIO period to its minimum value. Consequently, frequent parent changes tend to increase the overhead: the DIO period will continuously be reset.

Besides, continuous changes in the RPL routes also reflects its inefficiency if the environment is stable. Indeed, instability would mean that RPL is not able to find the *good* routes. It would mis-estimate the route quality, leading to oscillations.

Scientific challenge

Does RPL create stable and efficient routes? What is the impact of quality metric on the behavior of RPL?

This work represents the rest of the Ph.D. thesis of **Oana Iova** I have the great chance to co-advise with Thomas Noel (ICube, sept. 2011 - *).

4.6.1 Implementing the routing metrics with RPL

We implemented the different families of metrics to estimate their impact on the RPL behavior [Iov+13].

Number of hops

If we choose to privilege shortest routes in hops, no specific metric has to be included in the DIO. Indeed, the objective function would consist only in adding a constant (`MinRankIncrease`) to the rank of the preferred parent.

ETX

To save energy, we adopt a passive measurement technique: we estimate the packet delivery ratio without sending periodical `probe` packets. For unused links, we use the packet delivery ratio of DIO to estimate coarsely the radio link quality. For parents, we use the real unicast traffic transmitted to refine the radio link metric.

If the links are asymmetrical, this method would require time to converge: the DIO delivery ratio may be larger than the data delivery ratio.

LQI

We assume here the LQI is symmetrical for a radio link. Thus, we just have to measure the LQI of received packet t estimate the link quality.

Statistical estimation

These metrics correspond to instantaneous values. We must *smooth* their values to avoid sudden variations. We use an exponential moving average:

$$Metric(t+1) = \lambda Metric(t) + (1-\lambda) measure \tag{4.1}$$

with $metric(t)$ the previous estimation (at t) and $measure$ the new meure over the last period of time. The radio link quality is initialized to 1.0.

We use also a black list to discard bad radio links (i.e. their quality is under a threshold value) to avoid re-evaluate their quality periodically.

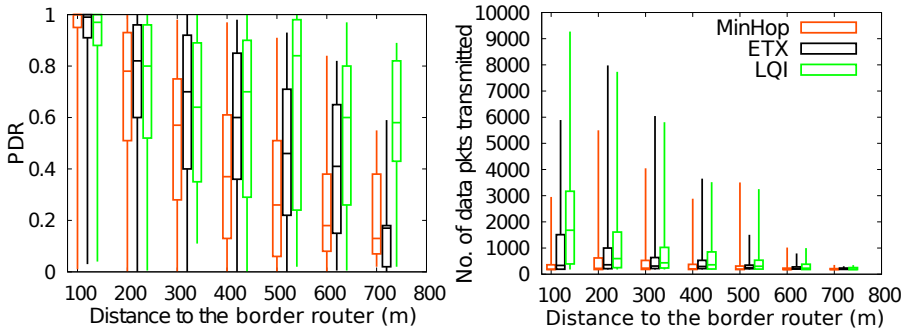
4.6.2 DODAG evaluation

We adapted the RPL implementation from Contiki [Dun+04] to the wsnet simulator. With simulations, we control finely the measures, the reproducibility, and we interpret more easily the results. If RPL is unstable in simulated environments, it will probably present at least the same instability in experimental conditions.

To isolate here the behavior of RPL, we used IEEE 802.15.4 without beacon. Indeed, the beacon mode creates itself some instabilities because of beacon losses, and because of the peaks of traffic at the beginning of the active part.

Table 4.1: Simulation parameters

Parameters	value
Duration	3600 s
Number of nodes	100
Traffic type & throughput	CBR, 5 pkt/min
Frame length	130 bytes (incl. MAC headers)
RPL	MinHopRankIncrease = 256
Trickle	$Imin = 2^7 ms$, $Imax = 16$, $k = 10$
Statistical estimator (exponential)	$\lambda = 0.9$
	blacklist threshold: $\leq 10\%$



(a) Packet delivery ratio vs. geographic distance from the sink

(b) Number of transmitted packets vs. geographic distance from the sink

Figure 4.11: Performances of RPL

We used the same PHY layer as previously, described in [CT11] (scénario FB6: shadow fading, fading = 1.97, std deviation = 2.0, $Pr(2m) = -61.4dBm$. The results are averaged over 20 simulations.

Local and global repairs of RPL are activated, and the used the default parameters as described in table 4.1. We chose $\lambda = 0.9$ to limit the impact of the dynamic (eq. 4.1).

The objective function is based on the minimum rank with an hysteresis function, using the metrics *MinHop*, *ETX*, and *LQI*.

Routing efficiency with a DODAG

We first measured the impact of the metric on the RPL efficiency (packet delivery ratio, delay).

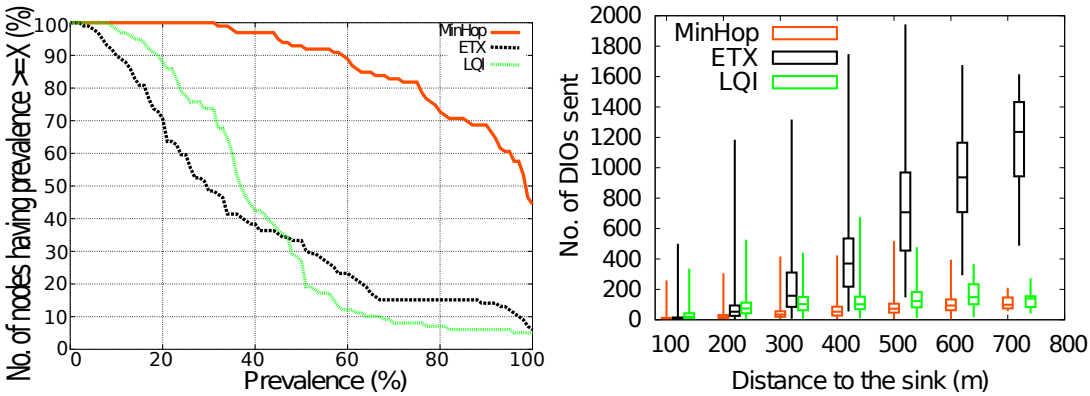
We present here only the most significant results of [Iov+13]. The packet delivery ratio of MinHop quickly decreases when we are farther from the sink (fig. 4.11a): the routes comprise often long and bad radio links. LQI achieves a better packet delivery ratio and avoids the weakest links. Finally, we can notice that the packet delivery ratio decreases for nodes far from the sink when using ETX. ETX seems not able to capture efficiently the radio link quality.

We coarsely estimated the energy consumption by monitoring the number of packets transmitted by a node (Fig. 4.11b). Indeed, a smaller number of packets means a larger sleeping period, and a better energy efficiency. With LQI, the nodes have more packets to relay, mainly because less packets are dropped. However, some nodes closer to the sinks have a peak of traffic to relay: the load is not well balanced. This bottleneck in energy will penalize the lifetime.

DODAG stability

After having observed the efficiency, we tried to capture the RPL dynamic: is the routing topology stable?

In a first time, we observed the route prevalence, i.e. the ratio of time during which we observe the same route (denoted principal route) [Pax96]. The prevalence is consequently estimated as the number



(a) Complementary cumulative distribution function of the route prevalence

(b) Number of DIO versus geographic distance to the sink

Figure 4.12: Performances of RPL with 100 nodes

of times where the principal route is used.

With MinHop, the DODAG is very stable (Fig. 4.12a). On the contrary, LQI and ETX exhibit a larger dynamic: the principal route is only used 20% of the times in more than one third of the nodes. We also verified that the problem persists even after having removed the initialization time (2 minutes and 1 hour).

As highlighted in figure 4.12b, ETX generates a large overhead: the DIO period remains very low, and increases the number of control packets.

4.6.3 Load balancing

By studying more finely the metrics, we have discovered that no metric efficiently balances the load in the network. Some bottlenecks exist and support most of the traffic.

The residual energy is the only one metric which takes into account this problem. However, this metric creates oscillations: all the nodes choose to pass through a node with large energy reserves, whatever the quality of the path is. This bottleneck will consume an large quantity of energy, and will soon be sub-optimal: its descendants will switch to another path. Intuitively, if $\Delta_{residual-en}$ is the unit of measure reported in DIO for the residual energy, a node will switch its decision as soon as the residual energy of the bottleneck node decreases by $\Delta_{en-residuelle}$.

We proposed a metric which identifies the bottleneck nodes [Iov+14b]. Besides, the radio link quality is also integrated in the metric: a node which owns a bad radio link will consume more energy to send the same amount of traffic. We proposed the *Energy Lifetime Bottleneck* (ELT) which estimates the lifetime of the most constrained node in the route.

By selecting greedily the parent with the best ELT, we balance the load (i.e. the energy). However, a single parent would lead to binary routing decisions: the whole traffic is transmitted to one unique parent. Besides, we would like also to avoid the instability created by estimation errors of the exact ELT value. We explore now how multipath may help to resolve these problems.

4.6.4 Limits and Perspectives

We analyzed here the impact of the metric on the RPL behavior. In particular, we isolated a problem of instability: even in a simulated environment, RPL changes continuously its routes, even with a model of stable links. Instead of balancing the load, it seems the current metrics are even impacted by the traffic itself. The more loaded is a route, the more the metric associated to the route decreases. RPL may switch to a worse route with less traffic. The trickle timer is continuously triggered, generating a larger number of useless DIOs.

We also highlighted the existence of a tradeoff between stability and efficiency: minhop is stable but performs poorly. On the contrary, ETX estimates more accurately the link quality, but maximizes the number of repairs in the DODAG.

These problems may be observed in simulations. However, it is logical to conclude the same phenomenon may occur in experimental conditions. We aim at conducting campaign of measures to verify our conclusions.

We did not yet solve the instability problem. We think that using several paths may represent a promising solution. Instead of pushing all its traffic to the preferred parent, a node would choose probabilistically its next hops. Weights would be computed according to the path quality offered by the associated parent. Besides, we *smooth* the changes to more accurately predict the future quality: we avoid changes in the decisions and estimations.

Finally, we aim at proposing also an *energy-balancing* routing solution. Announcing the bottlenecks introduces a certain variability. We have to limit the dynamic created by such feature.

4.7 Conclusion

In this chapter, we studied how the routing protocol may operate efficiently over a multihop wireless network. A geographic routing solution may minimize the amount of memory and takes local decisions. However, such solution leads implicitly on a localization system to find the geographic position associated to an id. Besides, geographic routing performs poorly in non homogeneous topologies. The radio link quality is also difficult to integrate in the routing decision.

We focused in this chapter on the WSN scenario. In a first time, we aimed at characterizing experimentally the environment by analyzing the measures obtained with the SensOrLab [Sen13] testbed. We highlighted a large variability in the neighborhood table, leading to an existential question: *what is a neighbor?* Besides, it is complicated to find a strong correlation between the RSSI and the radio link quality. Only a class of links may be isolated.

Then, we focused on the routing problem in this environment. When we execute a stack of standards, the cohabitation between the MAC layer (IEEE 802.15.4) and the routing protocol (RPL) is not so easy to achieve. In particular, the topology control of IEEE 802.15.4-2006 in beacon-enabled mode, eliminates any mesh. We propose to modify IEEE 802.15.4-2006, and in particular its topology control feature. We also proposed an efficient broadcast primitive in IEEE 802.15.4-2006, particularly important for RPL.

Finally, we studied the behavior of RPL, and in particular, the impact of the routing metric. RPL exhibits even by simulations a strong dynamic: the routes are never stable and oscillate. The routing metric seems even impacted by the routing choice, creating antagonist decision loops. Clearly, the interactions between the MAC and routing layers are not so easy. We are currently proposing a routing metric to balance the load, coupled with a multipath version of RPL to reduce the oscillations and to deal more efficiently with inaccuracies.

4.8 Related Publications

Journals

[Pav+13] Bogdan Pavkovic, Andrzej Duda, Won-Joo Hwang, and Fabrice Theoleyre. "Efficient Topology Construction for RPL over IEEE 802.15.4 in Wireless Sensor Networks". In: *Ad Hoc Networks* (2013).

Conferences

[Iov+13] Oana Iova, Fabrice Theoleyre, and Thomas Noel. "Stability and Efficiency of RPL under Realistic Conditions in Wireless Sensor Networks". In: *International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*. IEEE. London, UK, 2013.

[Iov+14a] Oana Iova, Fabrice Theoleyre, Mengchuan Zou, and Jialiang Lu. "Efficient and Reliable MAC-Layer Broadcast for IEEE 802.15.4 Wireless Sensor Networks". In: *Wireless and Mobile Networking Conference (WMNC).* IFIP/IEEE. Vilamoura, Algarve, Portugal, 2014.

[Iov+14b] Oana Iova, Fabrice Theoleyre, and Thomas Noel. "Maximizing the Lifetime of Wireless Sensor Networks with RPL". In: *Wireless and Mobile Networking Conference (WMNC).* IEEE/IFIP. Vilamoura, Algarve, Portugal, 2014.

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[Pav+11] Bogdan Pavkovic, Fabrice Theoleyre, and Andrzej Duda. "Multipath opportunistic RPL routing over IEEE 802.15. 4". In: *nternational Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM).* ACM. Miami, USA, 2011.

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[The+09c] Fabrice Theoleyre, Eryk Schiller, and Andrzej Duda. "Efficient Greedy Geographical Non-Planar Routing with Reactive Deflection". In: *International Conference on Communications (ICC).* IEEE. Dresden, Germany, 2009.

Chapter 5

Conclusion

In the last years, I mainly focused on the medium access control: how can we efficiently share the radio resource among a larger number of nodes, which do not sense the same medium activity?

I consequently studied how we may reduce the complexity of medium access with a kind of topology control. In particular, how could we construct a cluster-tree structure used for instance by IEEE 802.15.4-2006: which parent should choose a node to minimize the number of collisions and its energy consumption? A MAC layer with preambles, even as opposed to IEEE 802.15.4, may also exploit efficiently a topology control solution to *organize* the transmissions. Indeed, a node selects its neighbors after having constructed a WCDS to reduce the number of synchronization packets with short preambles. Finally, I also studied how C-MAC may optimize the medium access efficiency in a convergecast network. By using a k-tree core structure, we are able to differentiate the medium access between heavily loaded nodes and the other ones.

I also explored how multichannel may multiplex the transmissions to reduce the number of collisions and solve some of the pathological problems created by multihop topologies. I make a distinction between three scenarios, with an ascending number of constraints. In a first time, a multiradio network should be able to exploit efficiently several channels. We tried to answer a few questions: is channel hopping interesting in these conditions? How can we maintain a connected structures and offer broadcast primitives which offer a reliable delivery while avoiding deafness? If we focus on the single interface case, exploiting several channels seems more complicated. We proposed Molecular MAC, organizing the transmissions into a WCDS. Finally, we studied how we may enable a multichannel version of IEEE 802.15.4-2006 if we introduce an energy constraint.

More recently, I was interested on how we may exploit a multihop wireless network: could we make an abstraction of the MAC layer and design efficient routing protocols independently? In a first time, I aimed at characterizing the mutlihop wireless environment by analyzing the experimental data obtained with SensOrLab [Sen13] (Orange Labs). I also studied how the current standardized stack for the Internet of Things (RPL / IEEE 802.15.4) may be modified to make the protocols work together. A prefect layer isolation would create several problems: how does the routing metric reflect the MAC efficiency? Shouldn't the routing and MAC structure be identical? RPL constructs one DODAG per QoS criteria: should the association of IEEE 802.15.4 be removed? or should we construct a tree per criteria? How could we measure the impact of the routing metric on the MAC and vice versa?

In light of this work, are coming new challenges for me, constituting some natural evolutions. I will detail here a few of them.

5.1 What is a realistic radio network and how could we design efficient solutions?

The analysis of the experimental results obtained through [Sen13] have changed my mind about the *good* WSN assumptions. I confess to not being able to reply precisely to the question *what are the key characteristics of a wireless multihop network?*

Probably, networks deployed in urban, rural, indoor environments exhibit different characteristics. However, current solutions deal marginally with these specific properties, they assume a kind of genericity. Is such approach valid? Are the characteristics so different that another solution tailored to the specific needs is required? Such a conclusion would be very damageable: deploying a network would require to characterize finely the environment and would require consequently a very strong expertise.

It would be relevant to design modular protocols, activating some features when some characteristics are detected. A protocol would ignore asymmetrical links when they are not required for the proper functioning of the network. Else, smart acknowledgment mechanisms may activated.

This modular self-configuration is seldom studied in the literature. It would however simplify the deployment.

5.2 Guarantees to hide an network locally unstable

The absence of guarantee seems for me the most important pitfall of existing solutions in multihop networks. For instance, most of the papers do not adresse the fairness problem and focus only on the average case. In other words, the worst cases are uninteresting. For instance, some routes can never be discovered with geographic routing, i.e. some destinations are unreachable even if a connected path exists. Clearly, this appears unacceptable.

We cannot anymore propose protocols which only offer a *best-effort* mode in environments with fluctuating conditions. We must now design protocols to make the network reliable, and to hide its complexity. When we share a Wifi connection in commercial solutions, we have a kind of guaranteed throughput. It is lower but much more stable than in the *best-effort* case. We must guarantee this kind of performance also in multihop wireless networks.

The current trend created by IEEE 802.15.4e with a frequency hopping coupled with TDMA seems promising. This deterministic solution simplified the guarantee of performance. Recently, I worked with a master student in Inje University on the scheduling of anycast transmissions to make the communications more reliable. In parallel, I also initiated some studies using IEEE 802.15.4e-TSCH with two other master students in Basu University so that the network supports also a variable traffic.

The problem remains unchanged in mesh networks: their deployment is penalized by a poor fairness and an high instability in real conditions. It is essential to design stable solutions, cohabiting with e.g. TCP. Besides, the performance should not decrease suddenly as soon as the congestion point is reached. We have to implement a control admission solution, or implement a fast back-pressure mechanism to slow down the incriminated flows.

We have now to focus on minimal performance with some fairness constraints. We should be able to detect a congestion, and stop it, to avoid a domino effect. Most of the MAC layers (IEEE 802.15.4, IEEE 802.11) perform very poorly when saturation is reached: the medium access delay increases exponentially, and performance suddenly fall. We must guarantee the stability.

5.3 Interconnecting heterogeneous networks for a new usage

I presented here separately the two kind of networks I studied (mesh and sensor/actuator). However, I now envision te mesh networks as a terrific tool to collect the traffic coming from the Internet of Things. This wireless backbone would collect the traffic from multimedia sensors (video surveillance), to interconnect several bubbles of smart objects. Urban networks and smart homes represent key applications.

Thus, it is not possible anymore to design the networks independently. Load balancing should be global, using different and complementary technologies. We may create a unified communication graph,

dynamic (an interface is activated for a short time, for specific needs). How could we guarantee the stability of this kind of infrastructures, handling transparently different technologies (low-power wifi, wimax, IEEE 802.15.4, etc.) ?

Besides, the traffic would be heterogeneous. Measures collected by a WSN could be mixed with video surveillance flows. Elastic flows should be scheduled in the silence of the other ones, while limiting the energy consumptions of all the wireless routers.

Inter-penetrating virtual and real worlds predicts closer local interactions, and consequently a more localized traffic. Should we redesign entirely a decentralized Internet? Protocols such as IP use hierarchical addresses: are they the most accurate candidates for these applications? The current organization structures such as the DODAG of RPL are not anymore adapted: how could we create *localized* protocols with local features and impacts? Several questions remains unanswered.

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