UNIVERSITÀ degli STUDI di CATANIA

Dipartimento di Ingegneria Elettrica, Elettronica e Informatica

Dottorato di Ricerca in Ingegneria dei Sistemi
XXVIII Ciclo

Tesi di Dottorato

CONTEXT AWARENESS IN THE INTERNET OF THINGS AND ITS APPLICATIONS

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ABSTRACT

In the last decade the role of context awareness, traditionally focused on human to machine interaction, has broadened its perspectives to the machine to machine paradigma. The main goal of this dissertation is both to understand how to apply context awareness to "situations", perceived by smart devices, and to conceptually stretch context modeling to a dynamic contextualization in human to machine interactions.

The roots of the Internet of Things paradigma reside in the efforts reached in the Wireless Sensor Networks technology, mostly in data aggregation and in energy saving, and the adoption of multi-agent modeling has gained context awareness application to machine to machine interaction. A well defined methodology, previously applied to human to machine interaction, now can be adopted for smart devices, that behave like humans.

Another evidence of the emergence of the Internet of Things technology nowadays comes from the everyday life experience. The Internet of Things is the key for the practical implementation of innovative software systems for the ubiquitous computing. Thanks to all these technologies, Smart devices (like the Nest Thermostat[1] or the Apple Watch[2]) are currently more and more integrated among them and they

[1]http://www.nest.com/

[2]http://www.apple.com/watch/

are becoming "invisible servants" for final users. As a proof of this new technological era, we can think about how the usage of the Siri[3] tool has become an automated and unconscious mechanism in looking for a telephone number, in reaching a specific destination, or in driving home heating, to understand the potentialities of merging context awareness to the Internet of Things in a convergent and ubiquitous platform.

The enormous amount of smart devices, currently deployed in the world, have also to deal with an easy knowledge representation of sensed context, in order to provide new mechanisms to automate daily tasks, understanding the behavior of end-users within the surrounding environment.

On the other hand, the rapid growing number of smart devices deployed has a drawback in the future proliferation of high level context models, possibly coupled to lower context levels.

What emerges from the current study is the necessity to easy the management of multiple contexts, to be used by upper level applications. The dynamic contextualization solves this kind of issues, distinguishing from the total amount of features, captured from the surrounding environment, and the context model that is closely related to the issue to be solved.

Deep profiling on context aware usage enhances the development of context aware services, that can simply use an abstraction layer to properly manage underlying context models. What can be deduced is that the customization of context aware services to the user is a key process to narrow the gap between smart devices and their daily usage.

In this dissertation, the definition of high level scenarios have been determined by applying decision trees, for their huge potentialities expressed in dynamic context extraction.

[3]http://www.apple.com/ios/siri/

Applications of these concepts were used in developing management systems, addressed to an audience of experienced surgeons in breast cancer, covering surgical suggestions. The formal analysis of multiple datasets (related to the diagnosis of breast cancer), using interactive and navigable decision trees, showed the enormous potentialities of the system, both in knowledge representation (and its spreading), and in the identification of the context, considering the related decision support system mechanisms.

The conclusion of the research activity considers the emergence of context awareness in a future world, more and more full of smart devices connected among them, as an adaptive paradigm, for intra device optimizations and for final users' application level benefits.

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ONE

INTRODUCTION

1.1 Structure of this Dissertation

Human to machine interaction has seen a profound boost in the adoption of context aware services in recent years. Conceptually, the reasons beneath the adoption of this kind of approach is intuitively related in considering the "situation" of a specific user as a driver to provide an automated mechanism to properly understand how to "react" to specific environmental stimulations. The creation of innovative and ubiquitous services has pushed the need to build up a new architectural methodology for answering to human to machine interaction issues in a world of new smart devices, able to take part to the Internet of Things.

The role of smart devices is still more and more prominent, not only in considering human to machine interactions, but also in considering how they behave among each others and with the surrounding environment. Consider smart objects, that follow human behavior, as "living entities", expand the concept of context awareness to the machine to machine scenario. Multi-agent systems, that behave following human heuristic, for example, can now take part to the context awareness pattern.

Moreover, recent years have seen dynamic contextualization as a new and innovative approach for managing large amount of user related and environmental data in a meaningful way. What drives dynamic contextualization is the main goal of the related context aware service to be provided. What distinguish traditional context aware services from dynamic contextualization is how the set of features, taken as an input, are chosen. This make overlapping context, be treated, dynamically considering the needs of each specific context aware service to be provided.

Considering this preamble, this dissertation is structured as follows. A general overview on context awareness is described in chapter II. After that, chapter III explains the main issues related to the Internet of Things and Wireless Sensors Networks technology, with a brief overview of how context awareness can be applied to the Internet of Things scenario. What follows is an explanation of how "things" can become "living entities" in the Internet of Things scenario, through the implementation of human heuristics logic inside the devices. After that, in chapter V and VI, two applications of these concepts are provided. Chapter VII explains the main role of decision trees, considering context aware services, in knowledge management. Chapter VIII introduces and expands dynamic contextualization concept, to identify and overcome its intrinsic limits, related to the practical development of a fully dynamic contextualization system. An application of dynamic contextualization is provided in chapter IX, in which it is described a decision support system tool, for helping breast cancer surgeons choosing the best clinical treatment. Finally, chapter X outlines research results and future applications.

CHAPTER

TWO

TECHNICAL BACKGROUND ON CONTEXT AWARENESS

2.1 Introduction

During the last decade the Internet of Things has been growing with a huge amount of new smart devices deployment, causing an enormous generation of new data to be managed. These data need to be processed and understood to become valuable to human activities and smart devices need to find out new strategies to solve a broader category of problems such as data aggregation, network topology and energy efficiency. Nevertheless, interaction between the Internet of Things and user applications creates new operating scenarios, mostly related to current user situations and to the reactiveness of reasoning systems.

Context awareness represents a well established methodology to help smart devices to solve such kind of issues and its application to the Internet of Things scenario has been focused with great attention by the research community in the last years.

First applications of context awareness mostly affected desktop application and mobile computing in the past, but the last decade has seen the emergence of context awareness methodology, improving techniques to be adapted to the Internet of Things scenario. The main difference between desktop application scenario and the Internet of Things is the amount of data to be taken into account. Indeed, the growth trend of smart devices deployment shows that in the future we will be surrounded by a huge amount of smart devices [1] and it is not feasible to consider the processing of millions of smart devices, without an efficient mechanism to understand and filter the data to be processed.

Context awareness will play a crucial role in managing big data [2] and in understanding how to to process them, to achieve specific goals, like machine to machine interaction [3, 4] and knowledge representation. An important role in machine to machine interaction, related to self-awareness, has been given by cognitive networks. Indeed, a network is meant as "cognitive" if it has knowledge about how it is built, interconnected and if it owns mechanisms to spread this knowledge among the network, with a specific "semantic meaning" and reason [5].

Various frameworks have been developed to merge Context Awareness to the Internet of Things paradigma, but the design of most of them has been focused on the management of single context models. This represents a technological limit for new smart environments in which many kind of smart devices will coexist, making to surface multiple context models with different dynamic weights and different context layers among them. These limitations obstruct the emergent need of following user situations, to provide new context aware services, without an overcrowding of interaction between final users and the overall system. Moreover the issues related to the overlapping of multiple context models stray from the main target of the Mark Weiser's "The Computer for the 21st Century" [6], in which the Author states:

> *The most profound technologies are those that disappear.*

Indeed, next context aware solutions will have to disappear into the background, to be indistinguishable from everyday life, reducing the need to be managed by final users.

2.2 What is Context?

The definition of the term "context" is crucial to examine how "context awareness" works and how context can be seen by different perspectives, both in smart objects to human interactions and in machine to machine cooperation.

Before considering the context definition, it will be useful distinguishing between unprocessed data, sensed by a system, and data that could be considered as context information [7]. The distinction between this two concepts is quite easy, because context information differs from raw data, considering a processing step, able to check consistency of the specific data and focus on adding *meta data* to the data themselves.

The term context has been historically defined in many ways, most of the time starting from specific application scenarios, to abstract a general meaning of the term. In [8], for example can be found hundreds of different definitions of the term "context", that, according to the opinion of the Authors:

> *the content of all the definitions can be analyzed in terms of few parameters like constraint, influence, behavior, nature, structure and system.*

This means that the term context has been living an evolution in its definition, among the subjects in which it has been used. In the present work the term context has to be seen as a factor to manage complexity in ICT systems in a better way.

One definition of context can be found in [9], in which the Authors are focused on considering data sensed by Wireless Sensor Networks as a set of events, that could be discrete or continuous. Moreover in [9] context is defined as:

> *a set of interrelated events (also, called component events) with logical and timing relations among them.*

This context definition is strictly coupled with the reactiveness of the system, because an event may activate a rule in a specific area. Moreover, it is too much restricted to a specific technological field.

In [10] it could be found one of the first definitions of context, in which just location, nearby people and devices around are considered as a source of information:

> *Three important aspects of context are: where you are, who you are with, and what resources are nearby*

Moreover, the Authors state that:

> *Context includes lighting, noise level, network connectivity, communication costs, communication bandwidth, and even the social situation; e.g., whether you are with your manager or with a co-worker.*

Another famous definition of context can be found in [11], adding generic contextual capabilities to wearable computers], in which the Author states that:

> *context could be generally described as the subset of physical and conceptual states of interest to a particular entity.*

The previous definitions have been criticized by [12], because they do not provide a broader sense of context, mostly using synonyms to provide a formal definition. Instead, in [12] the term context has been defined as:

> *any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves.*

This is the most well known context definition in scientific literature because it makes easier for an application to state if a specific set of data could be used to describe or not a context, considering the interaction between users and the specified system.

On the other hand, this kind of definition does not suite well to be applied to multi agent systems, in which each agent acts according to human behavior laws. In this dissertation, the term context will be construed both for human to machine applications and for machine to machine applications that use human heuristics to perform specific tasks.

2.3 Context-Awareness

Context-awareness is a methodology that links context detection, performed by the system, to provide useful informations or services to the entity that is involved with the specific system.

The earliest context-awareness definition was introduced in [13] as:

> *the ability of a mobile user's applications to discover and react to changes in the environment they are situated in.*

This definition is too much coupled with the mobile computing scenario and it does not take into account the heterogeneity of other architectural solutions in which context awareness has been successfully applied. Another well known definition of context awareness can be found in [10]:

> *context-aware software adapts according to the location of use, the collection of nearby people, hosts, and accessible devices, as well as to changes to such things over time. A system with these capabilities can examine the computing environment and react to changes to the environment.*

This definition enlarges the focus of context awareness to a broader scenario. Indeed, in [10] it is clear that the context-awareness has to be intended as a system and not only as mobile application; moreover, as it has been shown in the previous paragraph, the definitions of context and of context-awareness are closely related to a few set of scenarios.

On the other hand the definition taken from [12] helps us to define in an abstract way context awareness:

> *A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task.*

The definition is not suitable to be applied to the multi agent machine to machine scenario, in which each agent acts according to human behavior laws.

Conversely, in this dissertation, the term context will be construed both for human to machine applications and for machine to machine applications that use human heuristics to perform specific tasks.

Moreover, it is necessary to specify a bunch of functional steps, related to context aware systems. In [14] Authors stated that crucial steps to build up a context aware system are:

- *acquisition;*

- *representation;*
- *delivery;*
- *reaction.*

Other features have been defined in literature to identify a methodology to build up a context aware system. State of the art context aware systems differ among them according to the level in which context awareness has been adopted. In [15] Authors specify this issue, formalizing three different approaches:

- *no application-level context model;*
- *implicit context model;*
- *explicit context model.*

While in the "no application-level context model" applications execute the acquisition, the representation and the reaction phase, in the "implicit context model" it is very common the usage of software components, like libraries or frameworks, to reach the goal. The "explicit context model", on the other hand, uses a layer to manage such kind of steps. The latter approach separates the application from the acquisition, representation, delivery and reaction steps. Of course, mixed methodologies may be applied in each application scenario.

At this stage, another useful definition for this dissertation is related to the meaning of Context Models. One of the most famous definition has been provided in [16]:

> *A context model identifies a concrete subset of the context that is realistically attainable from sensors, applications and users and able to be exploited in the execution of the task. The context model that is employed by a given context-aware application is usually explicitly specified by the application developer, but may evolve over time.*

Moreover, the Author gives a context attribute definition as:

> *an element of the context model describing the context. A context attribute has an identifier, a type and a value, and optionally a collection of properties describing specific characteristics.*

Both the definitions are very useful to understand the limits of current research in context awareness. Choosing the most suitable context model represent an issue in boundaries definition and responsibility, mostly delegated to the application developer. Moreover, the context model definition has to be treated in a particular way with a preliminary study of the application scenario and of the discriminability, related to each context attribute, in the context model definition.

As stated above, the crucial steps to build up a context aware system can be summarized in acquisition, representation, delivery, and reaction. The latter step can be implemented in different ways, such as [10, 11]:

- *presentation;*
- *execution;*
- *tagging.*

Each "reaction" of the context aware system is closely linked to the application in which context awareness has to be applied. The "presentation" consists in deciding which informations final users will be allowed to access. The presentation of context aware informations, for example, may be linked to users' locations. The "execution" reaction consists in the automation of tasks to be served, using context awareness as a trigger. The execution of context aware tasks is quite popular in home automation, to easy everyday life. The "tagging" reaction consists in the annotation of single smart objects data, to be fully understood and fused. Tagging will be more and more important in context awareness, to better manage issues, related to the treatment of big data in the next years.

2.4 Context Types

The acquisition step represent an important issue in context aware systems, due to the definition of context types to be managed and processed. In scientific literature context types have been primarily defined, following a physical measures categorization. For example, in [10] context has been categorized, using common questions. More specifically:

- *where you are;*
- *who you are with;*
- *what resources are nearby.*

So, this kind of categorization shows a specific perspective, related to the location of the user (both gps position, city names, addresses and common names), the social interactions among the users and other people and to resources that can interact with the specific users. Following this perspective, smart objects will be more and more important in context aware systems.

Another definition of context types, based on physical measures categorization, can be found in [12]. Authors distinguish between primary context types and secondary context types. More specifically, primary context types have been defined as:

- *location;*
- *identity;*

- *time;*
- *activity.*

On the other hand, Authors have defined secondary context types as a processed data, derived from primary context types. The given definition does not consider a huge amount of primary context types, essentially related to raw data generated by sensors, like temperature, pressure, etc. Moreover, this definition is not clear in scenarios in which the same context type is acquired directly from a sensor, or using an electronic record. While in the first case, the context type would be classified as primary context type, in the latter it would be managed as a secondary context type.

The "acquisition" step has been clearly categorized in [16], considering how context is fetched and managed. This definition included the following context acquisition categories:

- *sensed;*
- *static;*
- *profiled;*
- *derived.*

"Sensed" data are considered as measures that come from sensors deployed on the field. This kind of context data is clearly dynamic in its values over time. Pressure, temperature and lighting sensors are just few examples of this kind of context acquisition.

On the other hand, "static" context data are those that does not vary over time. For example, "static" data are related to the type of sensor or smart object that has been used in the context aware application, or manufacturer firm.

"Profile" informations are quite similar to "static" data, but behave with a slow dynamic over time. For example, the position of a specific sensor or smart object may change with a monthly rate.

Finally, "derived" data are those that have to be calculated, using primary context data. In other words, this definition explicitly extends the previous definition, related to the difference between primary and secondary context, formally abstracting both the sources of context data and the type of acquisition of those.

Using the latter consideration, in [17], authors conclude that context categorization can be divided in:

- *operational categorization;*
- *conceptual categorization.*

"Operational categorization" is related to the definition stated by [16] (previously described in this paragraph), while "conceptual categorization" relates to the differences between user-centric context and environmental context at a conceptual level [18].

A reconstruction of all these definitions has been given by [19]. The Authors consider primary context as:

> *any information retrieved without using existing context and without performing any kind of sensor data fusion operations (e.g. GPS sensor readings as location information)*

and secondary context as:

> *any information that can be computed using primary context. The secondary context can be computed by using sensor data fusion operations or data retrieval operations such as web service calls (e.g. identify the distance between two sensors by applying sensor data fusion operations on two raw GPS sensor values).*

Considering primary and secondary context types in this way, enables to settle in a simple way context data and to understand how to develop in a comprehensive way for the acquisition, representation, delivery and reaction phases.

2.5 Context Modeling

Context modeling represent an important task in the design of context aware systems. Indeed, choosing the right set of context data, related to the application scenario, is a complex task, that comprehend both acquisition issues of sensors or smart objects data and relationships among them. In [20], Authors indicate a set of features, related to context modeling definition, to be taken into account:

- *heterogeneity and mobility;*
- *relationships and dependencies;*
- *timeliness;*
- *imperfection;*
- *reasoning;*
- *usability of modeling formalisms;*
- *efficient context provisioning.*

"Heterogeneity and mobility" consist in the management of a large quantity of context information sources. More deeply, Authors specify that:

> *A context model should be able to express those different types of context information and the context management*

system should provide management of the information depending on its type.

As a result of the first feature, "relationships and dependencies" should be taken into account, for example, to easy the reaction of the system. Contexts may have both dependencies, related to primary and secondary categorization, or intrinsic dependencies, related to the specific application area.

"Timeliness" consists in storing and managing in a proper way past context values, and in the prognosis of them. Especially in machine to machine application, prognosis may be a relevant feature of the system. Considering both primary and secondary context, inaccuracy has to be considered as an issue to be solved. For example, in secondary context type, processing may increase the total amount of error of the context measurement. "Imperfection" should be taken into account for this reason. A very common example can be taken when calculating the exact position of a mobile device, provided with a set of orthogonal accelerometers and gyroscopes. Primary context, in this case, is represented by raw datas and secondary context is the orientation and the position of the device. What happens in real life scenario, when developing a Inertial Navigation Systems (INS) is that the error, related to raw data acquisition, dramatically amplify those, related to secondary context.

Moreover, the "reasoning" design feature is directly linked to the "usability of modeling formalism". The system has to understand how to react to a specific context, while actions to be formalized are also delegated to context aware system's designer. A clear formalization of the binding between the real world application scenario and context aware system represent a powerful gain to the maintenance of the context aware system itself. This is more evident in considering "efficient context provisioning". As stated in [20]:

Efficient access to context information is needed which can be a difficult requirement to meet in the presence of large models and numerous data objects. To select the relevant objects, attributes for suitable access paths have to be represented in the context modeling. These access paths represent dimensions along which applications often select context information, typically supported by indexes. These dimensions are often referred to as primary context, in contrast to secondary context, which is accessed using the primary context

2.6 Context Reasoning

Context reasoning represents an open issue for the pervasive computing scenario, as shown in [21]. Indeed, context reasoning process is related to the representation and processing of context, to achieve the best way in which adaptation rules and knowledge are managed. Conceptually, context data processing can be divided in three different layers. The lowest one comprehends techniques that use signal processing and machine learning to understand context, using raw data. The middle layer on the other hand is able to model contextualization, so that it can be represented in a proper way to the system. The last layer is the closest to the context aware application, and has to deal with triggering actions to be adopted in specific situations. Moreover, the top layer is responsable to provide a query language, so that final applications can use the underlying platform. Different solutions have been developed to provide a suitable query language for context management. The "context query language" [22] is one of the state of the art implementation of such kind of approach, but it has be emphasized the fact that the proper query language usually depends on the final context application. More deeply, a query language has to be integrated with the internal representation provided by the middle layer. Another best practice in the design of the top layer is related to publish / subscribe mechanisms, useful to abstract context acquisition from the application point of view. Indeed, while in traditional applications, in which context data flows are always available to the system, in mobility scenarios, primary contexts may not always be available. In this case, the role of the top layer is very important to abstract final applications from managing non-constant provisioning of sensors or smart objects data. In [23] it has been discussed this issue, focusing on the not stable nature of ad-hoc networking and on the availability of context data on the mobile environments. This means that the dynamic nature of context information has to be taken into account for building a suitable reasoning mechanism, able to adapt itself to the specific needs of contextual awareness. Moreover, contextual awareness has to deal with the importance of context data to be processed. This means that contextual awareness has to take into account not only data availability of sensors and smart objects, but it has to consider time-variant different sets of context data. Dynamic contextualization, described in chapters above, has to be linked both to the middle and to the top layer of the schematic representation mentioned.

The well known Winograd's work on context awareness specifically distinguishes two different aspects related to context representation. In [24], Author states that:

> *The hard part of this design will be the conceptual structure, not the encoding. Once we understand what needs to be encoded, it is relatively straightforward to put it into data structures, data bases, etc.. The hard part will be coming up with conceptual structures that are broad enough to handle all of the different kinds of context, sophisticated enough to make the needed distinctions, and simple enough*

to provide a practical base for programming.

It is clear that issues, related to context reasoning, should be considered in the definition of the most specific context modeling. The effort of context aware designer is preeminent in understanding and choosing the best practices to achieve context aware application's goals, distinguishing the management of context data representation from activation techniques.

Scientific literature have seen a huge amount of context reasoning techniques, mostly related to machine learning and pre-defined rules. A comprehensive survey of reasoning techniques adopted can be seen in [25]. The survey considers a total amount of 114 context aware applications, underlying how decision trees and other machine learning techniques have been used for the recognition and reasoning in context awareness. The following graph (Fig. 2.1), taken from the survey, shows the prominent role of decision tree in machine learning application to context awareness.

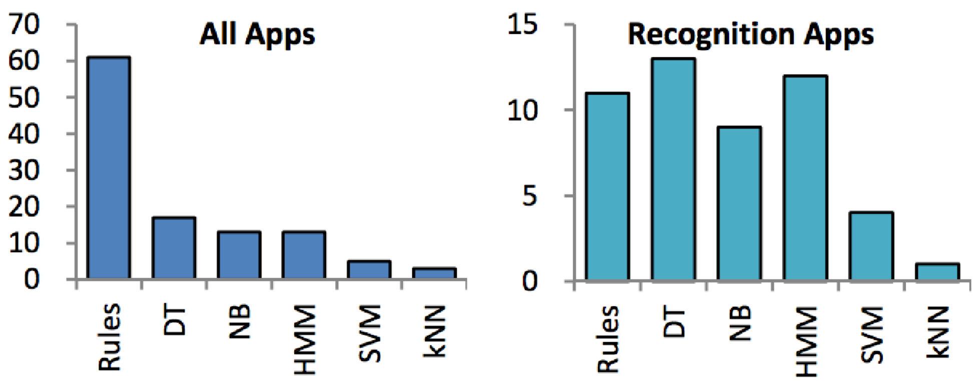

Figure 2.1: *Key: decision tree (DT), naive Bayes (NB), hidden Markov models (HMM), support vector machines (SVM), k-Nearest Neighbor (kNN).*

A more abstract categorization has been defined by [19], that divide the most known context reasoning techniques can be divided in six categories:

- supervised learning;
- unsupervised learning;
- rules;
- fuzzy logic;
- ontological reasoning;
- probabilistic reasoning.

"Supervised learning" represents a general family of algorithms that use labeled data to perform machine learning phase and to pilot the correctness of output predictions. Decision trees, bayesian networks, artificial neural networks and support vector machines belong to the "supervised learning" category. More specifically this dissertation will be focused on decision trees, as a preeminent methodology to build up trees that represent data classification.

The "unsupervised learning" family comprehends all the clustering algorithms like K-Nearest Neighbour [26] and Van Laerhoven Self-Organizing Map [27], that use data to classify context, considering similarity metrics to reach the goal. Applications of "unsupervised learning" can be found in [28] and in [29].

"Rule based" category on the other hand categories the simplest methodology to understand and react to specific captured context.

Moreover, "rule based" methodology is linked to traditional machine to machine scenarios, in which smart objects interact among them, using heuristic rules. In the next chapters a couple of applications, related to rule based context awareness, will be shown, emphasizing relationship with the Internet of things paradigma.

CHAPTER

THREE

WIRELESS SENSOR NETWORKS AND THE INTERNET OF THINGS

3.1 Wireless Sensor Networks Overview

3.1.1 Introduction

Sensor nodes are fitted with an on-board processor. These nodes communicate among them, sharing data collected or other vital information to monitor a specific environment. An ideal wireless sensor network should be networked, scalable, fault-tolerant, consume very little power, smart and software programmable, efficient, capable of fast data acquisition, reliable and accurate over long term, low cost and furthermore it should require no real maintenance [30]. The most well-known routing protocols for WSNs are [31]: flooding, gossiping, SPIN (Sensor Protocols for Information via Negotiation), directed diffusion, LEACH (Low Energy Adaptive Clustering Hierarchy), PEGASIS (Power-Efficient GAthering in Sensor Information Systems), GEAR (Geographical and Energy Aware Routing).

In general, an efficient routing protocol should perform the following targets [31]:

- data aggregation for power saving and in order to reduce the overall network overhead;
- dynamic clustering to avoid the quick energy depletion of cluster heads and hence to increase network lifetime;
- provide a threshold for sensor nodes on data transmission and dissemination, in order to help energy-saving by reducing unnecessary transmissions;
- multi-path selection dissemination to improve fault-tolerance and reduce the overhead of network load;
- self-configuration and adaptation of the sensor nodes to changes in network topology or environmental changes;
- time synchronization.

3.1.2 Applications

Areas of probable usages of WSNs are [30]: military applications, such as environment monitoring, tracking and surveillance applications; environmental monitoring, such as animals tracking, forest detection and flood detection, and weather prediction and forecasting; commercial applications, such as seismic activities monitoring and prediction, and smart environment applications; health applications, such as tracking and monitoring of doctors and patients in or out the hospitals by providing them with sensors; automation and control, such as robotics control.

3.1.3 Design factors of WSNs

The node has communication interfaces, typically wireless links, to neighboring domains. The sensor node also often has location and positioning knowledge that is acquired through a global positioning system (GPS) or local positioning algorithm. Sensor nodes are scattered in a special domain called sensor field. Each of the distributed sensor nodes typically has the capability to collect data, analyze them, and route them to a (designated) sink point. The following are some of the design factors of overall WSNs communications architecture as well as that of protocols and algorithms for WSNs [31]:

- *reliability or fault tolerance of a sensor*: is the ability to maintain the sensor network functionalities without any interruption due to sensor node failure; sensor node may fail due to lack of energy, physical damage, communications problem, inactivity, or environmental interference;

- density and network size/scalability: hundreds, thousands or millions of sensor nodes may be deployed to study a phenomenon of interest to users; the density of these nodes affects the degree of coverage area of interest, while the networks size affects reliability, accuracy, and data processing algorithms (scalability, on the other hand, may be enhanced by organizing network in a hierarchical manner, e.g., clustering, and utilizing localized algorithms with localized interactions among sensor nodes, while robustness to environmental changes, may be improved through self-organizing, self-healing, self-configuring, and self-adaptive networks);

- sensor network topology: the topology of a network affects many of its characteristics like latency, capacity, and robustness; densely deploying thousands of sensor nodes in sensor field requires careful handling of network topology maintenance;

- energy consumption: one of the components of sensor nodes is the power source which is limited enough; hence many researches are focusing on designing power-aware protocols and algorithms for WSNs with the goal of minimization of energy consumption. Some recommended solutions to these challenges are as follows: a reduction in the active duty cycle for each sensor node, defined as the ratio between active period and the full active/dormant period, a minimization of data communications over the wireless channel (i.e., aggregation, communication of network state summaries instead of actual data), and maximization of network life time (i.e., minimum energy routing);

- hardware constraints: sensor node consists of four main components: sensing unit, processing unit, transmission unit, and power unit; they may also have application-dependent additional components such as position/location finding systems, power generator, and mobilizer;

- data aggregation/data fusion: it is the task of reducing data size by summarizing the data into a set of meaningful information via computation while data are propagating through the WSN, it represents a solution to data congestion in sensor networks;

- self-configuration: it is essential for WSN to be self-organized; since the densely deployed sensor nodes in a sensor field may fail due to many reasons such as lack of energy, physical destruction, environment interference, communications problem, and inactivity, and new nodes may join the network. On the other hand sensor nodes work unattended in a dynamic environment, so they need to be self-configurable to establish a topology that supports communications under severe energy constraints;

- coverage: the sensor nodes view of the environment in which it lies, is limited both in range and in accuracy, hence the ability of sensor nodes to cover physical area of the environment is limited;

- connectivity: it is the ability to report the Sink node. A network is said to be fully connected if every pair of node can be communicated with each other either directly or via intermediately relay nodes. Therefore it is important to find the minimum number of sensors for a WSN to achieve the connectivity. Connectivity affects the robustness and throughput of the wireless sensor network.

3.2 Clustering methods

3.2.1 Clustering algorithms: issues and challenges

Clustering techniques have been introduced to address energetic constraints of sensors deployed in a large monitoring zone. In most applications of WSNs, sensors are usually remotely deployed in large numbers and operate autonomously. In these unattended environments, the sensors cannot be charged, therefore energy constraints are the most critical problem that must be considered. For this reason in large WSNs, sensors are often grouped into clusters to overcome sensors' energy depletion. In clustered networks, some sensors are elected as cluster heads (CHs) for each cluster created. Sensor nodes in each cluster transmit their data to the respective CH and the CH aggregates data and forwards them to a central base station (or sink). The clustered sensor nodes transmit messages within the clusters, while CHs waste more energy because of their message transmission cover longer distances (CHs to the sink) than the other sensor nodes in the cluster.

Some of the possible solutions to balance the power consumption of each cluster are the periodic re-election of CHs within clusters based on their residual energy, or also the rotation of the CH role within the clusters. Aggregating data at CHs via intra-cluster communication also helps in eradicating data duplication [32]. Clustering algorithms allow to improve the network performance as they address some of key limitations in WSNs such as: the limited energy of the nodes; network lifetime, scalability, data aggregation capabilities. Clustering can also preserve communication bandwidth since it limits the scope of inter-cluster interactions to CHs and avoids redundant exchange of messages among sensor nodes. A CH can schedule activities in the cluster so that nodes can switch to the low-power sleep mode most of the time and reduce the rate of energy consumption [33]. Clustering algorithms however have some disadvantages such as additional overheads during CH selection, assignment and cluster formation process. Many clustering algorithms have appeared in the literature, and the aim of this section is to highlight their commonalities, strengths and weaknesses [32]. The following are the components of a clustered WSN: sensor node, clusters, cluster heads (CHs): CHs are the leader of a cluster. CHs are often required to organize activities in the cluster. These tasks include data-aggregation, organizing and relaying the communication schedule of a cluster, the base-station (it is normally the sink in a WSN), and the end-user [34]. In general, there are two main steps in clustering, which are CH selection and cluster formation. The main issues in selecting CHs are: the distance between CHs and the BS to ensure that CHs are not too far from the BS, which would make the communication among CHs and that between the CH and the BS too expensive; uniform CH distribution so that CHs are not cluttered, in fact it can cause long distance between non-CH nodes and their corresponding CH, causing high energy consumption for intra-cluster communication. CH re-selection or rotation is another concern in clustering. Other aspects to be considered are: the residual energy in a sensor node to be elected as a CH, and the time delay, that is how long it takes to select a CH and to form a cluster. This parameter could mean the communication disruption during that period [32].

3.2.2 Classification criteria of clustering techniques

In classifying clustering techniques first it must be considered the network model and some of the relevant architectural parameters and their implications on network clustering. WSNs consist of three main components: sensor nodes, base-station and monitored events. Most of the network architectures assume that sensor nodes are stationary, while sometimes it is necessary to support the mobility of base-station or CHs; in the latter case, clustering become very challenging since the node membership will dynamically change, forcing clusters to evolve over time. The monitoring operation can be either intermittent or continual depending on the application: monitoring intermittent events allows the network to work in a reactive mode, simply generating traffic when reporting, whereas continual events require periodic reporting and consequently generate significant traffic to be routed to the sink; this could result in an overload of the CHs, then a rotation of the CH role may be required; in the case of intermitted events, adaptive clustering techniques could be adopted. In addition to network dynamics, it is also important to consider in-network data processing and the topological deployment of the nodes, that affects network clustering. According to the deployment, in particular in self-organizing systems, the position of the base-station or of the CH assumes a key role in terms of energy efficiency and performance, hence optimal clustering becomes a pressing issue to enable energy efficient network operation. In some setups CH selection may be constrained according to the different functionalities associated with the deployed nodes. In networks of homogeneous sensor nodes in terms of computation, power and communication, CHs are selected from the deployed sensors and carefully tasked in order to avoid depleting their energy rather quickly. The communication range and the relative CH's proximity to the sink are also factors to be considered in the choice of CHs; sensors' communication range is usually limited and a CH may not be able to reach the sink, furthermore sometimes multi-hop routes are preferred than direct communication with the base-station, although nodes are able to communicate directly with the base-station. Other constraints on the clustering process may arise from specific WSNs requirements since some nodes may be selected for special tasks or empowered with distinct capabilities. It may then be required to either avoid such specific nodes to conserve their resources or limit the selection of CHs to a subset of these nodes.

The main objectives for network clustering typically are load balancing, fault-tolerance, increased connectivity and reduced delay, minimal cluster count, maximal network longevity, therefore they may be considered as criteria for CH selection and node clustering [33].

3.2.3 Clustering algorithms for WSNs

Clustering is an effective mean for managing a large number of sensors in WSNs; since scalability is one of the main advantages of clustering techniques. The following are some of the most popular clustering algorithms, focusing on the distributed ones:

- LEACH (Low-Energy Adaptive Clustering Hierarchy). LEACH is one of the most popular clustering algorithms for WSNs. It uses a distributed approach; a node decides to be a CH with a certain probability p and broadcasts its decision. Each non-CH node determines its cluster by choosing the CH that can be reached using the least communication energy. The rotation of CH role allows to balance the load within each cluster in the network [33]. LEACH converges completely in a fixed number of iterations, regardless of the number of nodes, then it is a constant convergence time algorithm [32].

- EEHC (Energy Efficient Hierarchical Clustering). EEHC is a distributed and randomized clustering algorithm which aims to maximize the network lifetime. CHs collect the sensors' readings in their individual clusters and send an aggregated report to the base-station. EEHC consists of two phases: single-level clustering, in which each sensor node announces itself as a CH with a certain probability p to the neighboring nodes within its communication range, these CHs are called volunteers CHs. Any node within k hops range of a CH that receives such announcements and is not itself a CH becomes the member of the closest cluster. If the announcement does not reach to a node within a preset time interval, the node will become a forced CH assuming that it is not within k hops of all volunteer CHs; multi-level clustering, the process is extended building h levels of cluster hierarchy. EEHC reduces significantly energy consumption for network operations and such reduction will depend on the parameters p and k of the algorithm [33].

- EECS (Energy Efficient Clustering Scheme). In EECS the CH election is based on the residual energy. For each round, CH candidates compete to become CH; the competition provides the broadcasting of residual energy of the candidates to neighboring candidates and if a given node has more residual energy than the neighboring, it will become a CH [32]. EECS approach is used to address the problem due to higher transmission energy required by the cluster at a greater range from the base-station than those that are closer. Furthermore, EECS allows for a better distribution of energy in the network, a better resource usage and extends the network lifetime.

- CLUBS. It exploits the local communication to efficiently aggregate nodes into clusters, in which the convergence time depends on the local density of the nodes. The clustering approach is based on the following features: every node in the network must belong to some cluster; maximum diameter of all clusters in the network should be the same; every node within the cluster should be able to communicate with each other using only nodes within that same cluster, that is clusters should support the intra-cluster communication [33]. The algorithm satisfies several other constraints that occur in large distributed environments such as the limited or no topology knowledge of the network, and also the algorithm does not need global IDs.

- ACE (Algorithm for Cluster Establishment). ACE is a self-organizing cluster algorithm for WSNs. The main idea of ACE is to assess the potential of a cluster node as a CH before becoming a CH and steps down if it is not the best CH at the moment. The two logical steps in ACE algorithm are "spawning" of new clusters and "migration" of existing clusters [35]. Spawning is the process by which a node becomes a CH, while Migration is a process in which the best candidate for being CH is selected. The algorithms consists of multiple iterations: at the beginning all nodes are unclustered, then they become followers or CH. The overall effect would appear as clusters are applying a repulsive force to spread out and reduce their overlap. In addition to the repulsive effect, there is an attraction mechanism between clusters related to their degree of overlap. ACE exhibits perfect scalability, moreover it is fast, robust against packet loss and node failure thereby efficient in terms of communication [33].

- LCA (Linked Cluster Algorithm). LCA is a distributed clustering algorithm that avoids communication collisions among nodes and uses TDMA frames for inter-node communication, with a slot in the frame for each node. Basically, the LCA approach was designed to be used in the small networks (less than 100 nodes). In such small networks, the delay between the node transmissions is minor and may be accepted. The proposed distributed algorithm aims to form clusters so that a CH is directly connected to all nodes in its cluster. LCA is thus geared for maximizing network connectivity. The algorithm assumes synchronized nodes and time-based medium access. A node is assigned the slot in the frame that matches its ID [35].

- FLOC (Fast Local Clustering service). FLOC is a distributed clustering technique that produces non-overlapping and approximately equal-sized clusters. The nodes are classified according to their proximity to the CH into inner-band (i-band) and outer-band (o-band) [33]. A node can communicate reliably with the nodes that are in the inner-band (i-band) range and unreliably with the nodes in its outer-band (o-band) range. FLOC favors i-band membership in order to increase the robustness of the intra-cluster traffic. FLOC is fast and scalable and it also exhibits self-healing capabilities since o-band nodes can switch to an i-band node in another cluster [35]. Furthermore, FLOC achieves re-clustering within constant time and in a local manner, and get locality, in fact each node is only affected by the nodes within two units.

3.3 The Internet of Things Overview

The evolution of Internet has seen in the last decade the emergence of a growing number of smart devices and of machines, interconnected among them, able to communicate and cooperate in many application scenarios. This means that the traditional approach, based on wireless sensor networks, has been overcome by the disruptive effect of big data generation and of a florid rainforest of technologies, able to perform most of the ubiquitous computing concepts.

The Internet of Things represent this new technological wave, in which things are seen from the different perspective of smart devices in a global interconnected network. The boost in wireless communication has pushed this idea in current deployments, in which smart devices can now benefit of stable connections to the network.

To understand what smart devices are, a clear definition has been given in [36], in which authors focus on the main features related to the physical characteristics, the communication abilities, how a device could be uniquely addressable in the network, and how a smart device can be able to sense the surrounding environment and process them. Following this definition, smart devices:

- have a physical embodiment and a set of associated physical features (e.g., size, shape, etc.);
- have a minimal set of communication functionalities, such as the ability to be discovered and to accept incoming messages and reply to them;
- possess a unique identifier;
- are associated to at least one name and one address. The name is a human-readable description of the object and can be used for reasoning purposes. The address is a machine-readable string that can be used to communicate to the object;

- possess some basic computing capabilities. This can range from the ability to match an incoming message to a given footprint (as in passive RFIDs) to the ability of performing rather complex computations, including service discovery and network management tasks;

- may possess means to sense physical phenomena (e.g., temperature, light, electromagnetic radiation level) or to trigger actions having an effect on the physical reality (actuators).

The value of the technology and of the applications related is still growing and it can be clearly demonstrated in how industry is going to develop more and more Internet of Things solutions, as shown in 3.1:

The main roles of Internet of Things in context awareness reside in how it has been developed, to let smart devices to be addressable and to be able to expose services to final users. Moreover, the machine to machine interaction has been enhanced, showing new possibilities to manage autonomous complex systems. This means that context aware applications can easily be implemented in such a scenario and can be gained in the enhancement of two solutions:

- machines to humans interactions;

- machine to machine interactions.

While the machine to humans context aware solutions has been largely discussed in literature, machine to machine reaction to context has not been focused in the same way, despite the scientific literature has produced solutions in the adoption of self-awareness to modeling agents for cognitive networks [37]. A definition, taken from [38], groups these aspects:

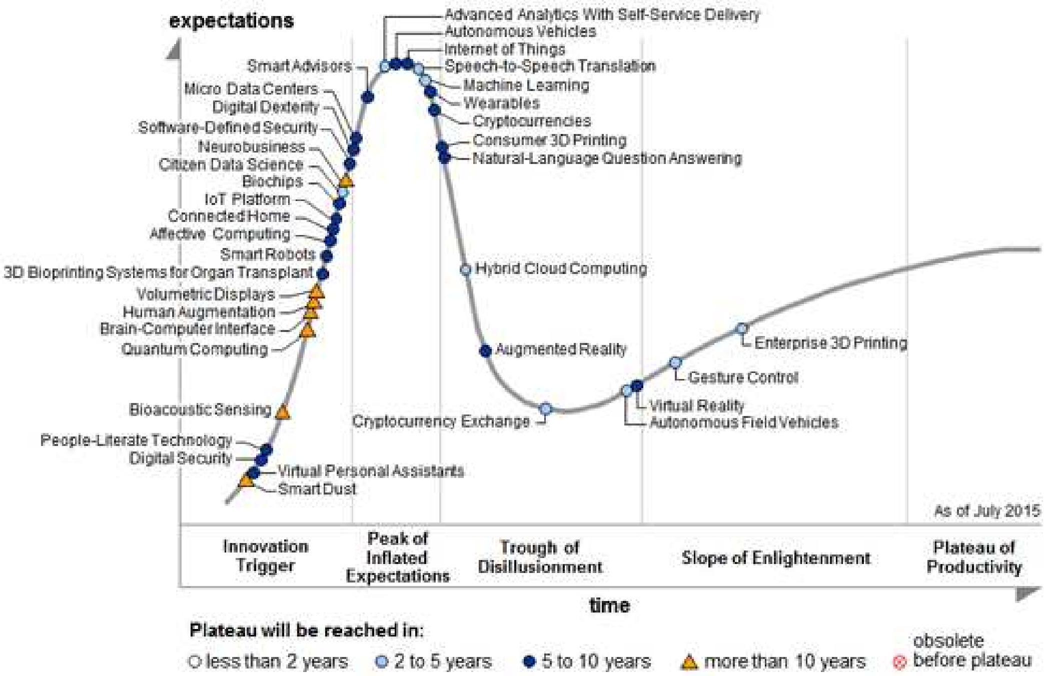

Figure 3.1: *Gartner's Hype Cycle for Emerging Technologies, 2015*

> *Things have identities and virtual personalities operating in smart spaces using intelligent interfaces to connect and communicate within social, environment and user context.*

The consideration of "things" as living entities opens new perspectives on how context awareness should be considered, because it allows to extend profiles, usually related to the traditional context awareness methodology in the human to machine interaction mode, to the completely different patterns of machine to machine interaction mode. In this way "things" act following human behavior scheme.

CHAPTER

FOUR

SMART DEVICES AND LOCAL INTERACTIONS

4.1 Introduction

Wireless sensor networks (WSNs) are large networks made of many autonomous low-power, low-cost and small-sized sensor nodes. WSNs use sensors to co-operatively monitor complex physical or environmental conditions, such as motion, temperature, and sound. Such sensors are generally equipped with data processing and communication capabilities to collect data and route information back to a sink. The network must possess self-organizing capabilities since positions of individual nodes are not predetermined. Cooperation among nodes is the dominant feature of this type of network because sensor nodes use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data [34]. Sensor nodes can be either thrown in mass or placed one by one in the sensor filed, hence the deployment may be deterministic or self-organizing.

The future of WSNs is the integration of bio-inspired ideas, hierarchical clustering methods, and sociological models and concepts such as sense of community and the satisficing theory to form a social network model [39] and [40].

These methods are crucial for the development of context awareness among nodes.

This will be possible using the node intelligence to allow network to self-organize itself into communities deciding how to join, through an aggregation/rejection mechanism, trying to keep the key requirements regarding the quality of service, efficiency, security, trustability and computational power. For this reason it has been developed a new model on a multi-agent system, where a single agent is an intelligent node, exploiting the Internet of Things approach [41], described in the next chapter. After that it is necessary to introduce the heuristic model to give to the node the ability to decide about the interactions with other nodes obtaining a social smart behavior of the network. This approach is characterized by the assessment of the trustability value and the risk perception value for each node; this will rule the formation of the community and the aggregation/rejection mechanism of the nodes.

The aim of [41, 42] is to propose algorithms based on the models mentioned above, in order to emphasize the importance of the concept of cooperation and sense of aggregation to group or community. These models accept and follow the natural tendency to aggregate and reject each other according to a bio-inspired and self-organized approach, following an aggregation/rejection model, applying a clustering method to a multi-agent model, based on heuristic decisions, in order to get a "satisficing" model. This methodology allows to increase the global knowledge in a WSN with nodes characterized by bounded conditions such as limited time, limited knowledge and limited computational power. In the next section the reasons that led me to adopt a bio-inspired approach in designing context awareness in [41, 42], will be explained.

An overview of wireless sensor networks, given in the previous chapter and a dissertation about applications and the main design factors, introduce technical challenges, described in [41, 42], like clustering methods, to focus on the state of the art methodology. Moreover, it is intended to talk about the sense of community and the Simon's concept of satisficing. The next section is focused on heuristics and Internet of Things, to explain how to use these concepts in the model. This explanation is very important to focus the attention on the presentation and description of the "It measures like me" algorithm (IMLM) [41] and of the "A Energy-Preserving Model for Wireless Sensors Networks Based on Heuristic Self-Organized Routing" [42].

4.2 The bio-inspired approach

The bio-inspired approach allows to solve certain problems and meet specific requirements, such as reliability, information load, risk management and energy saving, under conditions of limited computational resources, time constraints and low overall knowledge. Such kind of approach has been used as a model that relates the cooperation of multi-agent systems, the intelligence of the node, according to IoT, and also the "satisficing" concept of heuristic decisions. What are the analogies between our system and a biological scenario? A biological system is characterized by the following features: high complexity; high connectivity; communication, cooperation and coordination; relation with other systems of the same nature and finally relation and communication with external environment. For this reason it is clear that a power aware WSN, that has to send aggregated information related to single clusters, is a complex system similar to a biological one. The Dressler's approach, proposed in [43], is composed by: identification of analogies, understanding and engineering. The identification of analogies step is summarized in the following scheme:

- High complexity → IoT intelligence node.
- High connectivity → sense of community and social behavior + aggregation model.
- Communication, cooperation and coordination → multi-agent system + heuristics + trustability model.
- Relation with other systems of the same nature → logic of similarity + heuristics + information load.
- Relation and communication with external environment → social and human cognition.

The proposed approach tends to solve decisional issues (through heuristics), cognitive aspects (using the proposed trustability model), security problems (exploiting risk perception model), and shared knowledge management (using a controlled information load). The understanding and engineering steps will be treated in the following sections.

4.3 Sense of community and satisficing

The context proposed in this chapter concerns sensor nodes deployed in a general environment, joining in self-organized hierarchical communities to trace back information required to the sink. The nodes, deployed in the environment, initially assume a sensing attitude of neighborhood that corresponds to the natural tendency of an individual who wants to make inferences about unknown aspects of an unknown context. The node will begin to detect the context features to have good perception of the neighborhood following the logic of similarity.

4.3.1 Aggregation, trustability and empathy

Following the Homan's idea that the more frequently persons interact with one other, the stronger their sentiments of friendship one another are apt to be, the similitude hypothesis is made plausible by empirical evidence that the stronger the tie connecting two individuals the more similar they are, in various way [44] and [45]. In the aggregation state the nodes assign to each other a trustability value. Initially, the assignment of this value will be done randomly, following the logic of an encounter of nodes and the natural process that gives rises to a different "empathy mechanism", between different nodes. The "empathy mechanism" explains the process for which we trust in a different way of one rather than another, without a apparently reasonable logic. At the beginning, this mechanism is to align groups according to the logic of the first encounter, then the trustability values, also linked to the risk perception, will follow a different logic. By creating communities, and by assigning different values of trustability, nodes will establish weak ties and strong ties with its neighbors, respecting the hierarchy.

4.3.2 Strong and weak ties

A fundamental weakness of sociological theory is that it does not relate micro-level interactions to macrolevel patterns in any convincing way. The target of Granovetter's paper is to relate the network analysis with macrophenomena such as diffusion, social mobility, political optimization and social cohesion in general [44] and [45]. Following Granovetter's theory, it can be considered, for example, three nodes deployed, A, B and C; suppose that A-B and A-C are strong ties. Hence, the relation C-B will probably exist because of the common strong ties with A. This can show us that, the way of aggregation through strong ties gives us a measure of the probability of future changes in the network, unwilling to counteract this natural tendency, the network autonomously evolve in the future by actions of rejection, which will force a new aggregation and the formation of a new groups for sense of community. The strong ties will help to maintain the structures stables, and maintain a consistency in the calculation of the measure to be sent. Instead, weak ties allow and encourage flexibility and dynamism among the various groups/communities. Nodes hierarchically higher manage faster than nodes hierarchically lower. The nodes may decide to reject other nodes under certain conditions. This process creates a real network of relationship, social and dynamics in order to maintain a sense of community for interests, in this case for similar measures. The communities are created by aggregation for similar nature, and the hierarchy by the sense of community.

4.3.3 Sense and perception of community

In the paper [40] and [46], the dynamics of the force of the sense of community is described by various elements and by a process by which these elements work together to produce the experience of sense of community. The sense of community scale (SCS) is used to focus on communicative behaviors and attitudes at the community or neighborhood level of social organization. Those levels depend on informal interaction, safety, prourbanism, neighboring, preferences and localism [40] and [47]. One of the most interesting definitions of sense of community is that, through this force, the modern society develops communities around interests and skills, rather than around locality. In [40] the authors have described the sense of community in four elements: membership, influence, integration and fullfillment of needs, and shared emotional connections. Table 4.1 describes the analogies of the four elements of Mcmillan-Chavis theory and the features of the IMLM model and Energy-Preserving Model [40, 41, 42].

McMillan-Chavis theory	IMLM model
Membership	Become a CHL/CH0
Influence	Rejection process
Integration, fullfillment of needs	Aggregation, satisficing
Shared emotional connections	Sharing value of temperature

Table 4.1: *McMillan-Chavis theory and IMLM model.*

4.4 Heuristics that make WSNs smart and things

4.4.1 Inference, heuristics and satisficing

How do nodes deployed in a topology make inference about unknown aspect of a context? The possible approaches [48] could be three: the first follows the Laplacean demon theory that considers the mind as a supercomputer, with unlimited time, unlimited knowledge and unlimited computational power. This follows the classical view that human inferences rules are those of probability and statistics. The second approach is fully heuristic which sees inference as systematically subjected to human error: this perspective is diametrically opposed to the classical rationality. The issue is much more complex because it would identify the conditions under which the human mind seems to be more rational or more irrational. The heuristics would suggest the inability to achieve the complexity of the classical canons of the models of rationality. The third approach achieves a balance of compromise between the ones just described, and it is the approach of a controlled heuristic on which we build our proposed model in this paper. The latter follows the theory of Simon [39], which is based on the concepts of "bounded rationality" and "Satisficing". Simon starts from hypothesis that information systems of processing should have the need to satisfy rather than optimize. Hence, the term "Satisficing", that is the union of "sufficing" and "satisficing", is suitable with our model and with models that, in general, deal with conditions of limited time, limited knowledge and limited computational power. The theory of "bounded rationality" focuses on some appropriate human minds in the environment in which they live, only if they have the right perception of their limits, according to a cognitive, ecological and saving logic, and only if they still meet the target. Therefore, this approach remains heuristic but not at all, and finds the right compromise between the heuristic decisions and the sense of community, control strategy and suitable criteria. The heuristic approach is a solution to the problems, that do not rely on a clear path, but rely on intuition upon temporary circumstances in order to generate new knowledge. To overcome the simple heuristics in the model related to the bounded rationality of Simon, it is also necessary to rely on the good sense of the community in decision- making, and add trustability and risk perception. The heuristic models that in general rely on bounded rationality, follow the two aspects defined by Simon, that is, cognitive mode and ecological mode [39], [49] and [50]. In models such as "Two Alternative Choice Tasks", there are two types of inference: inference from memory, decisions are taken considering declared knowledge, studies, memory and history; inference from given, decisions are made considering data and information extracted from a calculation or data extracted from an experiment. Following the process suggested by Simon, it should be involve only the first type of inference. The initial process, and probably the most natural one, is to base decisions only on those we have acquired in the past. In proposals, taken from [41, 42], the component "inference from memory" is represented by an array that keeps track of our past contacts. This allows us to make inductive inference during aggregation to a community. Obviously, the inductive inference needs to

Aggregation/rejection	CH_x
Inference from memory cue value 1: trustability	$\pm$
Inference from memory cue value 2: risk perception	$\pm$
Inference from givens cue value 3: measure value (temperature)	$\pm$
Inference from givens cue value 4: variance	$\pm$

Table 4.2: *Cue values for inference on aggregation/rejection.*

be investigated in relation to the surrounding environment, topology and context of the communities created. This type of psychological inference replaces the complex classical rationality with a simple and plausible mechanism. Exploiting intelligent insights about unknown properties, based on indicators of uncertainty, a subject must know the "cue values" that can be linked to the target variable in order to make inference, in a positive or in a negative way. Each "cue" has also a validity which indicates the frequency with which the cue correctly predicts the target defined according to the environment. The "cue values" represent criteria, and suggestions used for assessment in order to achieve the targets. In Table 4.2 it is shown the cue values for our algorithm.

Each cue will be characterized by a validity and a discrimination rate. In proposals, taken from [41, 42], after an initial self-organized sensing phase, the node join together and form communities, considering the similarity measurement of temperature, trustability, risk perception and variance values, or taking into account energy levels and quality of radio signals.

4.4.2 Trustability and risk perception

Multi-agent systems principles can be applied to the heuristics previously described: the set of nodes will be deployed in a certain environment and will interact each other using organizational rules that follow the hierarchical clustering, and exploiting two principles of multi-agent system, organization and cooperation. Cooperation is related to the interactions among agents. It is the fundamental feature of multi-agent system where the overall system exhibits significantly greater functionality than the individual component [51]. Cooperation allows to reach the target through coordination and conflict that regulate the community and which result in the aggregation and rejection processes. In this way, it is possible to get an autonomous system, multi-agent and self-organized. Nodes become smart objects which have different communication, information and processing capabilites. Thus, it is possible to leverage on an Internet of Things (IoTs) model, that is a worldwide network of interconnected objects uniquely addressable [52] and [36]. The future Internet aims to integrate heterogeneous communication technologies, both wired and wireless, in order to contribute and to assert the concept of Internet of Things [53]. The IoTs is playing a key role in several scenarios such as: healthcare and wellness, home, building and industrial automation, energy efficiency, smart grid infrastructure, environmental monitoring, RFID infrastructure, smart WSNs, smart transport automation. A smart object is able to understand events and human activities occurring in the physical world, and has the ability to converse with the user in terms of input, output control and feedback [53]. With IoTs it is possible to create interesting opportunities for novel information services. Smart objects' true power arises when multiple objects cooperate to link their capabilities. Starting from a WSN, design choice of the proposals in [41, 42] converges in the introduction of a heuristic model that allows to reach the perfect compromise between ”satisficing” [39] and the compliance by smart objects in bounded conditions. The heuristic will allow to explain how the nodes make decisions, come to judgments and solve complex problems with incomplete information [54]. The purpose of the proposals in [41, 42] is to use fast and frugal heuristics, that make inferences. The main advantage is that using heuristics it is possible to reduce the complexity of the tasks in operations much more simple and immediate. People have two systems for making decisions in rapid intuitive error prone and slower reflective statistical mode.

When an agent interacts with other agents, it can or not trust on their neighbors. The trustability, in [41, 42] proposals, is implemented as a personal recording one by one that measures the trustability level of the node with which it must interact. The model the presented in [54] is taken as a reference, by adding the empathy mechanism and contextualizing it in accordance with our problems. What should be considered in the models [41, 42], as well as α_{ij}, that is the dynamical memory for the trustability of i on its partner j, also the parameter A_i, that is the risk perception, which regulates the value of trust in the nodes of the community. Furthermore, an oblivion mechanism is considered to update the network in terms of knowledge. This results into the need of the network to forget periodically, and update dynamically. In summary in [54], the heuristic is used to balance between the costs and the risk of being infected, in my proposals [41, 42] is used to balance between the bounded condition and sending reliable parameters, not neglecting risk and energy saving, as in Fig. 4.1.

Therefore, introducing all the features mentioned above, nodes become more ”human”, as well as smart and self-organized. Nodes are able to decide, then the limited conditions allow to obtain resolute decisions that in terms of community, and interactions between them

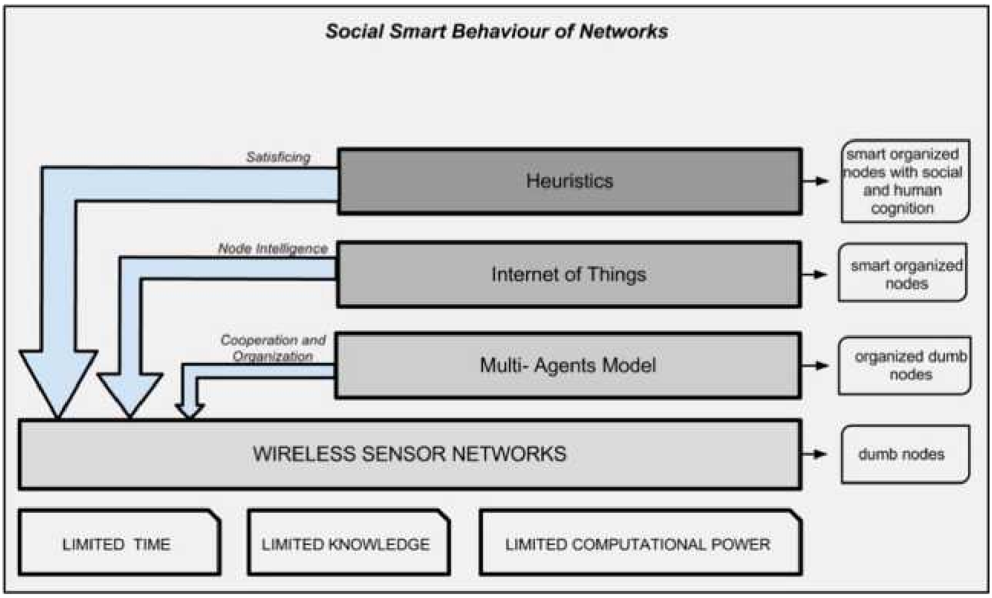

Figure 4.1: *Steps to have social smart behaviour.*

allow to have a social smart behavior.

CHAPTER

FIVE

THE *IT MEASURES LIKE ME* ALGORITHM

5.1 Introduction

The "It measures like me" (IMLM) algorithm is applied in WSNs, in which a large number of sensor nodes is deployed in a extended region to monitor and measure some parameter such as temperature. IMLM aims to reduce power-consumption and to introduce a social smart behavior of the network. IMLM fuses an aggregation/rejection model, in terms of clustering, with a heuristic multi-agent model related to a single node. IMLM uses heuristics to mitigate the speed of node rejection with a decision taken in a short lap of time (limited time), using a reduced amount of information (limited knowledge) and consuming low battery as possible (limited consumptional power) [48] and [49]. The main assumption of the clustering process takes advantage from the first law of geography: "everything is related to everything else, but near things are more related than distant things" [55]. The basic idea is that we can aggregate a large amount of known nodes in a WSN. The aggregation mechanism concerns with radio visibility of couples of nodes. The algorithm approach is self-organized and consists of nodes ”instinct” to aggregate themselves to other communities while the rejection policy is managed hierarchically by cluster heads (CHs). The proposed model follows rules similar to those ones of cohesive attraction or cohesive force, that is the action or property of how molecules sticking together, being mutually attractive. The cluster aggregation is similar to the molecular aggregation based on the instinct to follow its own nature. The node is attracted by neighborhood inside its radio range and it will aggregate naturally with one of them. The same thing happens in the case of oil in a glass of water: the two liquids split each other to form two different clusters, then they mix again cause an external force that is represented in the algorithm by the CH decision to reject one or more CHs. IMLM is based on a multi-agent model that considers abstract entities called ”agents”, that work autonomously in the algorithm in different ways according to their states and roles. These roles depend on hierarchical levels and on the internal state: idle, cluster head (CH), that could be a CHL or a CH0, going up the hierarchical ladder, and still climbing the sink node.

5.2 Description

Before focusing on the operation of the algorithm, the following are the different types of messages exchanged between the nodes in the various steps with a brief description for each of them:

- Cluster Head Notification Message (CHNM): notification message sent by a neighboring CH.
- Node Affiliation Message (NAM): node affiliation to a CH.
- Measurement Message (MM): it allows nodes to communicate a single measurement or a mean value.

- Variance Request Message (VRM): it allows CHs to ask "children" for sub-community variance values: it is set "true" when it is needed to forward the message, otherwise it is "false".

- VRM Response (VRMR): the sub-community sends variance value.

- REJection Message (REJM): it allows CHs to reject a child: "true" is used to reject it, while "false" is used to maintain the child.

The IMLM operation is described as follows and figures are used to outline graphically the various steps as in Fig. 5.1 and Fig. 5.2.

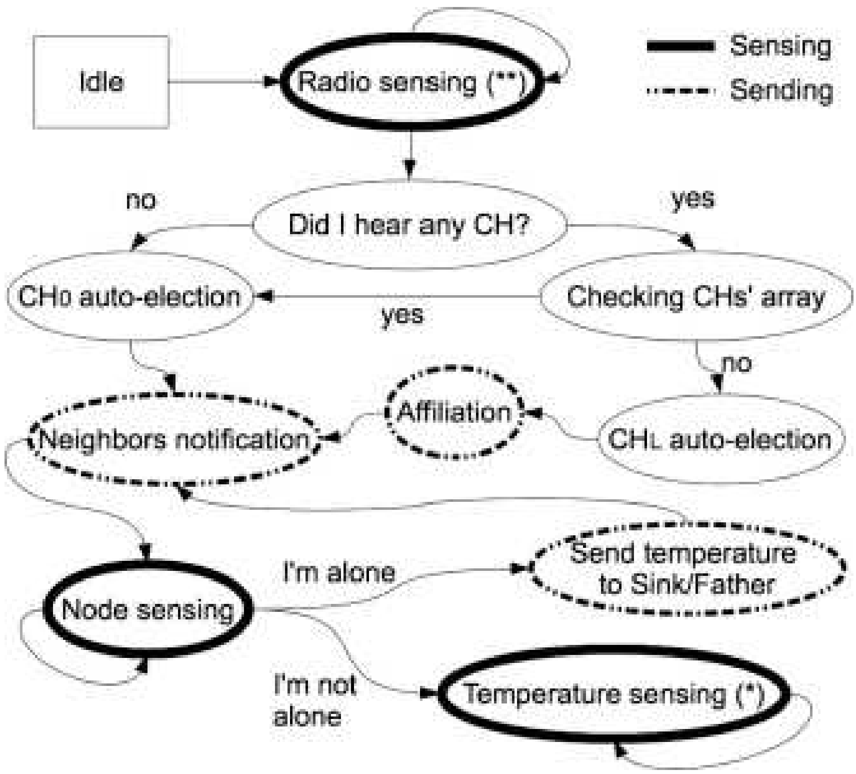

Figure 5.1: *Algorithm description-aggregation.*

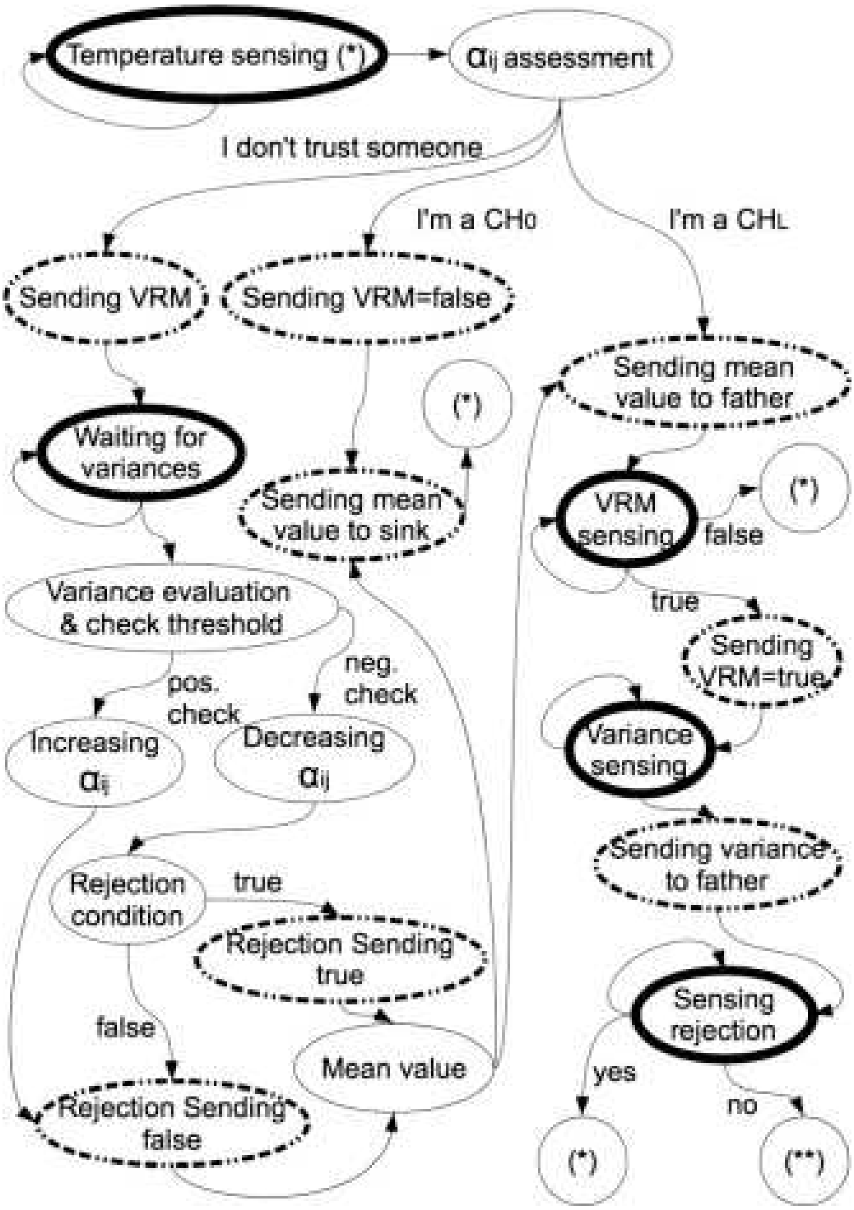

Figure 5.2: *Algorithm description-heuristics and rejection.*

At the beginning the node stays in the idle state and listens to CHs via radio sensing for a random period of time. The node listens to CH Notification Messages (CHNMs) to know if there are CHs in the neighborhood. Both in the case in which an idle node does not recognize that in the case in which recognizes the presence of a CH that rejected it in the recent past, it will auto-elect itself as a CH0. Otherwise, if the node finds an available CH, it will become a CH with a lower hierarchical level (CHL) and it will send a Node Affiliation Message (NAM) to the "father" (i.e., the node of higher hierarchical level). Hence, the node notifies to the neighborhood its actual state in both cases using CHNM messages. After "Neighbors notification", the node will wait for NAM messages from its children and it will register their identities (IDs). CH will have to associate a random trustability value, in the interval between 0 and Ai for the empathy mechanism described early in the above sections. If the CH is alone and if it is a CH0, it will send its measured temperature to a sink node, otherwise if it is a alone CHL, it will send it to the father. Instead if the CH is not alone, it will wait for Measurement Messages (MMs) from children; MM can be either single measurements or mean values of sub-communities.

The IMLM algorithm uses a heuristic mechanism based on trustability estimation directed from CH to its children. For this reason, the CHs evaluate the trustability among all children and relate sub-communities. In the trustable case, if the CH is the root of the hierarchical tree (CH0), it will send a Variance Request Message (VRM) set to "false" to children, and the mean value of the whole community to the sink. The next step is to return in the "temperature sensing" state. If the CH has a lower hierarchical level, it will send the mean value of its community to the father and it will wait for a VRM. A received VRM, set to "false", allows the node to come back to a temperature sensing of its sub-community, while VRM set to "true" forces CH to forward the request (VRM) to its children. In the latter case CH has to wait for a VRM Response (VRMR) to collect variance values from sub-communities. Then it calculates its local variance value to be sent to the father. It will listen to the REJection Message (REJM) to see if it still belongs or not to the community. The α_{ij} assessment allows to identify untrusted children. This condition occurs when the related α_{ij} is less than the risk perception, A_i, as discussed before in the other sections. In this case, the autonomous agent will be "scared" of specific sub-communities, so it will ask them for updated variance values that result in a local new variance value. It is needed to evaluate also variances related to trusted sub-communities; these values will be estimated weighting them with a coefficient that is inversely proportional to the trustability value and directly proportional to the last variance value related to the sub-community. The variance calculation is based on [56]. The Ward's method aims to minimize the inner-cluster variance. The variance of a community is calculated as:

$$S = S_w + S_b \tag{5.1}$$

where S is the matrix of total variances and co-variances, S_w the matrix of internal variances and co-variances, S_b the matrix of external variances and co-variances. If we consider a uni-variate measurement and two clusters, 1 and 2, the global variance will be calculated as follows:

$$\sigma_{tot} = \sigma_1 n_1 + \sigma_2 n_2 + [(\mu_1 - \mu_{tot})^2 + (\mu_2 - \mu_{tot})^2]/(n_1 + n_2) \tag{5.2}$$

where σ_1, σ_2 are variance values of the two communities; μ_1, μ_2 are the corresponding mean values; n_1, n_2 represent the number of nodes in each cluster. The new community variance value will be compared with a fixed threshold. If the check is positive, the specified trustability, related to the sub-community, will be increased of a fixed quantity V_α, otherwise, it will be decreased of the same quantity.

In the latter case, the CH will have to see if the sub-community is still suitable in order to send a REJection Message (REJM), "true" or "false", according to the new trustability and A_i values. If the trustability value is less than $-A_i$, the corresponding sub-community will be thrown away, otherwise it will be maintained. The rejected node will register the last CH in a specified scheduling queue, not to allow the association to a "old" community for a certain period of time. Each CH in the queue is affected by a oblivion factor, following a negative exponential function $(1-\lambda)^{\tau}$. If the oblivion factor reaches a fixed threshold, the associated CH will be thrown away from the queue. The last step consists of the mean value calculation, considering all the "alive" sub-communities, and finally the sending of it to the father or to the sink. Each CH0 communicates a mean value to the sink, that forwards information to an elaboration center, integrated with GPS positions of the community. The elaboration center will reconstruct a measurement map, using interpolation algorithms like Kriging [57].

CHAPTER

SIX

AN *ENERGY PRESERVING MODEL* FOR WSNS ROUTING

6.1 Introduction

There are many types of routing and forwarding algorithms for WSNs, characterized by different kinds of actions about how to reach the destinations. In general, an efficient routing protocol should perform aggregation, clustering, self-organization and cooperation for power saving and to increase network lifetime; it should also consider a threshold for sensor nodes in data transmission in order to get energy-saving, and a multi-path dissemination to improve fault-tolerance. An energy-preserving model for wireless sensors networks has been proposed in [42], based on a heuristic and self-organized routing. It has been considered a network with specific nodes which need to send information to just one of a set of sinks. In order to make simpler and reduce the communication flow that would produce a large amount of energy consumption, each node routes information exploiting a cognitive behaviour of its own neighbourhood, without using traditional routing protocols that could produce large routing tables, for a huge amount of sensors. The hierarchy follows a trend ranging from the sink to the probable sources. From the latter, following the hierarchy created previously, each node will choose the next hop according to an heuristic mechanism, based on trustability, goodness perception of the path and battery level of node. The heuristic approach considered within the model will allow to explain how the nodes take decisions to solve complex problems with incomplete information using trustability level and perception, following a top-level strategy that leads to solve problems exploiting this underlying heuristic, so that it results in a heuristic approach.

6.2 Energy-Aware Routing Protocols

Routing or Forwarding of data packets in WSNs can be divided into three categories [58]: flat-based routing, hierarchical-based routing, location-based routing. In flat-based routing nodes have the same role and responsibility in forwarding/routing data, while in hierarchical-based routing, decisions are influenced by the hierarchical rank of sensor nodes. Furthermore, another classification of routing protocols is based on how routes are created [59]. In a proactive approach all routes are created in advance and updated regularly; in a reactive approach routes are computed only when they are required, and a hybrid approach is a combination of these two ideas. The most well-known routing protocols for WSNs are [31]: flooding, gossiping, SPIN (Sensor Protocols for Information via Negotiation), directed diffusion, LEACH (Low Energy Adaptive Clustering Hierarchy), PEGASIS (Power-Efficient Gathering in Sensor Information), GEAR (Geographycal and Energy Aware Routing). In general an efficient routing protocol should perform data aggregation for power saving, dynamic clustering to increase network lifetime, a threshold for sensor nodes on data transmission and dissemination, in order to help energy-saving, multi-path selection dissemination to improve fault-tolerance, self-configuration and adaptation of the sensors nodes to changes in network topology and finally time synchronization.

6.3 Proposal

Sink nodes in WSNs are able to receive messages from other nodes and collect various kind of data. Usage of multiple sinks is related to power consumption reduction in WSNs, as a mechanism to increase the system lifetime, as shown in [60], for this reason the topology follows a hierarchical organization in which the highest role is delegated to sink nodes. Three phases have been identified: Topology Setup, Data Sending and Heuristic Approach. The model tries to satisfy the need of reaching the nearest sink node, considering heuristic decisions to reduce the overall power consumption of the nodes in the network and network's errors. The aim of the proposal is to use simple network signaling and light logic to maximize network lifetime.

1) Topology setup phase: Topology setup phase is initialized by sink nodes, which represent 0-level hierarchical nodes (HN0), sending a topology setup frame to their neighbors, at a certain time interval, $T_{topologysetup}$. Each HN0's neighbour will become HN1, storing node IDs of previously identified HN0s and, in turn, they will send the topology setup frame to their neighborhood. Topology setup frame (TSF) is defined as follows (Table: 6.1):

TREQF	Se	Re

Table 6.1: *Topology Setup Frame*

Network's nodes, without a specific role, will listen to topology setup frames (TSF) and they will become L-level hierarchical node, choosing own level L as the minimum of the levels of nodes which have sent it a topology setup frame:

$$L = min\ (nodes\ levels) + 1 \tag{6.1}$$

Consequently the HN_L will store IDs of the HN_{L-1} nodes so that it will be able to use one of them to reach a sink, as shown in Fig. 6.1.

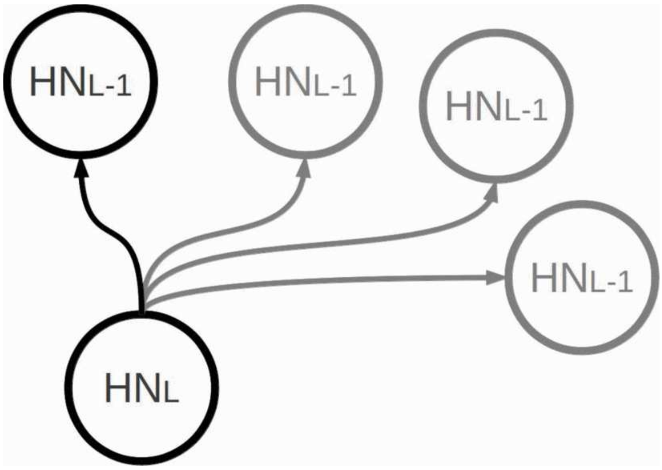

Figure 6.1: *Each node could reach multiple "higher" level nodes*

The HN_{L-1} black circled node is the "delegated node", chosen in a heuristic way described in the next section, by HN_L node to send data to the sink.

2) Data Sending: When a HN_L node needs to send data to a sink, it will use the delegated node, using a Data Frame, defined as follows (Table: 6.2):

TRESF	Se	Re	Battery Level	Link Quality

Table 6.2: *Topology Setup Frame*

At each Data Frame (DF), the node will store, the Sender (Se), the Receiver (Re), the last Data Frame Counter (DFC), the payload of

Data packet, and in the check phase (explained below) it will consider the values of link quality indicators such as RSSI (Received Signal Strenght Indicator) and LQI (Link Quality Indicator) related to the received frame. Fig. 6.2 and Fig. 6.3 represent a network with two sinks and two different paths.

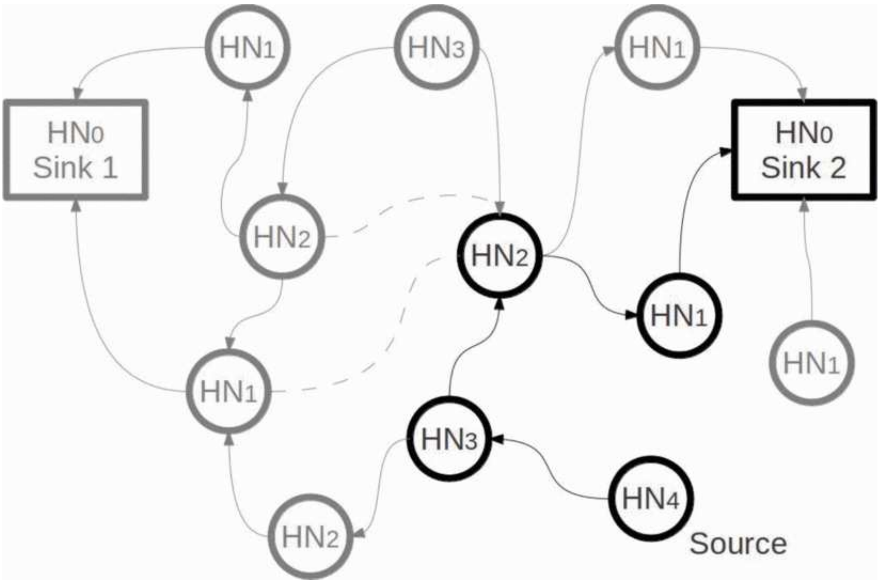

Figure 6.2: *HN_3 routes on the right.*

3) Heuristic Approach: If a source node needs to send data to a sink, it will refer to one of the hierarchical upper level neighbours. It will choose the specific neighbour, using a heuristic approach, similar to [54], taking in account both battery level and communication quality. A generic node i stores a risk perception level, A_i, that intuitively represents a mean "trouble" level with neighbour nodes. Each node will store a trustability level, α_{ij}, related to each "higher" level hierarchical node and they will use the most "trustable" node in the neighborhood to reach the sink. The choosen node will be called "delegated node". Considering a generic node i, and its delegated node j, if the trustability level, α_{ij}, related to j is greater than the risk percep-

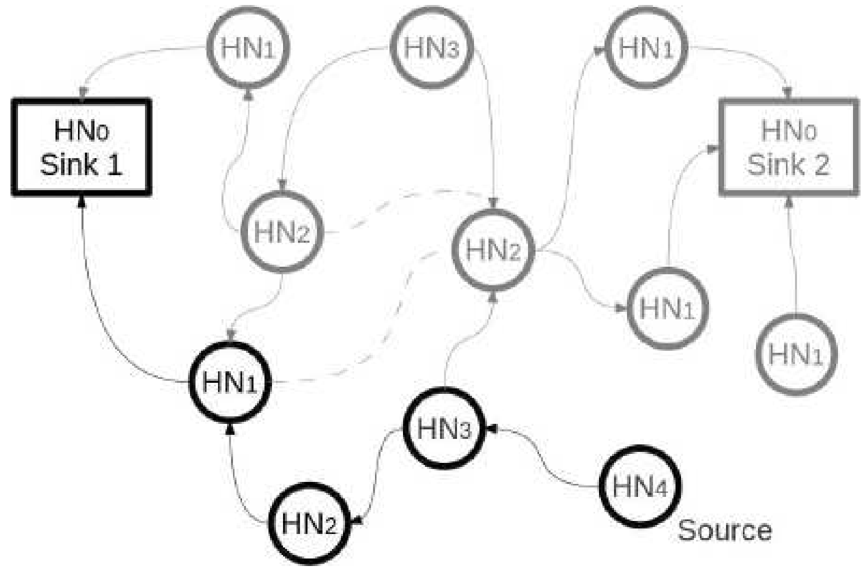

Figure 6.3: *HN_3 routes on the left.*

tion perceived by i, A_i, it will send data to node j without considering j's battery level, or connection quality between them.

$$Condition: \ if \ \alpha_{ij} > A_i => i \ sends \ data \ to \ j \tag{6.2}$$

The model considers nodes with a finite memory, so they "forget" their history, following an "Oblivion Mechanism"; as a consequence risk perception and trustability will be updated at certain time steps, as follows:

$$\alpha_{ij} = \alpha_{ij}(1 - r_\alpha)^\tau; A_i = A_i(1 - r_A)^\tau \tag{6.3}$$

In this way the model will force nodes to check model's parameters against neighbors and refresh knowledge perceived. The r_α parameter represents the rate of decrease of the Trustability Level, likewise r_A is the rate of decrease of Risk Perception, and τ are the time steps before the present time. If node i does not trust nobody for the Oblivion Mechanism or Negative Checks (explained below) it will start a "check phase". The check phase consists in asking to delegated node the link quality indicators (RSSI, LQI) of the last Data Frame and the battery levels to each "higher" level node, using a Trustability Request Frame (TREQF) and a Trustability Response frame (TRESF).

Battery levels and connection quality parameters will be used to recalculate trustability levels related to each "higher" level neighbour. This is how the correction of trustability level related to the delegated node is calculated:

$$\alpha_{ij_{next}} = \alpha_{ij_{previous}} + v_{\alpha}(C'_{weight}C_{ij} + B'_{weight}b_j) \tag{6.4}$$

where C_{ij} is the parameter related to connection quality between i and j, C'_{weight} is the weight related to the importance of considering the connection quality. Moreover, b_j is equal to 1 if the battery level of node is lower than the quantity: $Meanbatterylevels - Standard\ Deviation_{battery\ levels}$, otherwise it is equal to zero. It has been choosen such kind of threshold ($Standard\ Deviation_{battery\ levels}$), to consider the global amount of energy in the neighborhood and its distribution among nodes. B'_{weight} is the weight related to the importance of considering battery levels in the model. B'_{weight} and C'_{weight} are design values that will be choosed according to the specific target to obtain. The A_i factor is a key parameter in the model because it guides the behaviour of a node, according to the amount of α_{ij}, following a heuristic approach. v_{α} is a key parameter because it rules how the trustability should grow up, so it is a design parameter. For this reason, periodically, at a certain time step $T_{perception}$, nodes will recalculate the risk perception perceived, using the following relation:

$$A_{i_{next}} = A_{i_{previous}} + v_A(\frac{B'_{weight}b_{nc} + C'_{weight}C_{nc}}{totalchecks}) \tag{6.5}$$

where b_{nc} represent the total number of negative checks related to battery levels and C_{nc} represents the total amount of negative checks on network connection quality. $Totalchecks$ is the amount of total checks, both for battery and communication "rightness". v_A is a another key parameter because it rules how the Risk Perception should grow up and it represents a design parameter as v_{α}. Future works will simulate this proposal model to find out the best values of design parameters. Different topologies will be considered and different sinks distribution, aiming to minimize nodes' energy consumption, to identify bad data frames sent to sinks and to evaluate the performance of the proposed model.

CHAPTER

SEVEN

DECISION TREES OVERVIEW

7.1 Introduction

The classification of instances, described by different features, is a well known issue. A lot of different algorithms have been developed in literature, to understand how to manage knowledge of large datasets. Classification algorithms can be divided in two subgroups: unsupervised learning algorithms and supervised learning algorithms. The main difference between the two groups resides in considering unlabeled instances for the unsupervised learning and labeled instances for the latter one. Another difference between unsupervised and supervised learning is related to the underlying logic that is used in classification. While in unsupervised learning samples used for the training phase are not labeled, in supervised learning it is possible to evaluate error in the prediction phase, using specific evaluation metrics. The development of context aware systems obviously needs a supervised learning approach, both for profiling of users' behavior and for specifically classify the environment set. Many supervised algorithms have been developed, considering possible connections between multiple features and different kind of features values. For example, continuous valued features, rather than binary ones, enhance issues in the classification phase.

As stated in [61], the classical approach related to the development of a supervised machine learning classifier can be summarized in figure 7.1:

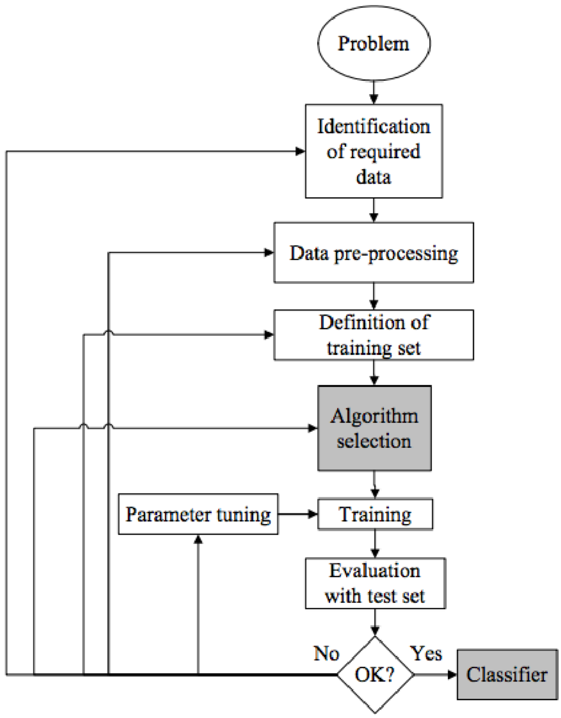

Figure 7.1: *Supervised machine learning development schema*

The first phase is closely related to the definition of the application problem. This phase is most of the time delegated to domain experts, that have to be focused on defining the boundaries of the problem to be solved and on specifying the goals to be reached. The next phase is the identification of the required data to be processed. This step has the role to understand the most discriminant features to be measured and processed, to properly classify and manage the knowledge of the system. Many machine learning algorithms try to automatically understand how to discriminate important features from those that does not have an evident correlation this the attributes to be classified, but in general this process is generally delegated to the designer of the classifier. Data acquisition and pre-processing is another important step in the design of a supervised classifier. Data to be considered could be incomplete or could be affected by noise. The pre-processing step is crucial both for the definition of the correct training set available and for choosing the proper classification algorithm to be learned. Indeed some algorithms outperform classification phase with cleaner data and can be better trained with specific considered percentage of test set, taken from the overall amount of samples. The most important phase in the classification process design is the one that comprehends the training phase, the evaluation with the test set and the parameter tuning. These steps are crucial for building efficient classifier, related to specific application scenarios. More deeply, the evaluation metrics are linked to the application scenario, and have to be considered, taking into account known relationships between features and attributes to be properly classified.

For this dissertation it has been considered the role of decision trees in managing representation and reasoning context features in context aware services, for the extraordinary abilities to graphically and easily show relationships between features, considering the discriminability of each feature during the evaluation of the classification phase. Moreover, another important ability of decision trees resides in the fact that the decision tree approach is able to automatically select the importance of different features, taken from the considered environmental scenario. Context aware systems have to dynamically select the importance of each feature that are able to sense, in order to provide the best inferences to final users or to properly manage machine to machine interaction. As show in previous chapters, decision trees have been chosen in many context aware systems, but the scope of this dissertation is to overcome the traditional approach in using decision trees in managing context awareness. Indeed, as previously shown, the traditional approach is too much linked to the context aware designer. This means that most of the time the importance of features to be processed could be misunderstood or overestimated in the evaluation process. The Internet of Things era, on the other hand, opens new challenges in managing not only a huge amount of data, but also very different features to be processed and automatically understood. Decision trees could be a valid solution to the issues previously stated for the behavior both of the learning phase and of the classification task. Indeed, the navigation of the classification tree enables the classification step to consider just features that contribute to understanding the most suitable classification, using a hierarchical organization of branches. Each decision branch is defined by different values of features selected at the design phase.

The root of the decision tree is always chosen as the most discriminative feature of the training set. How a feature is meant as discriminative is linked to the metric adopted by the specific decision tree algorithm. After having chosen the root node of the decision tree, the training set is divided into subsets, following specific values of the root feature node. Iteratively, each subset is considered as a new training set for the rest of the features taken from the feature set. The iterative nature of decision trees classifiers is very useful in simplifying the development of the algorithms to be used in the classification phase. The training phase always ends with considering the feature class that has been adopted in the design phase, as the goal of the classification process. The evaluation phase, previously discussed has the role to understand how the classifier built, using this approach, is able to classify both training data samples and test / unseen data samples. Classifiers that show fewer evaluation error in classifying training data, than in classifying test dataset are said to overfit training data. The most common approach to overcome this kind of issue, could be performing learning state, considering a pre-defined amount of error, related to the training dataset, without enhancing the accuracy of the system. Moreover, for decision trees, pruning phase better the classification phase. Pruning phase consists in choosing a decision tree that performs the same error in the evaluation phase, compared to another with more leaves. Pruning methodology has been surveyed in [62], and is obviously an important phase in context representation. Indeed, representation of a fewer set of leaves make decision trees more efficient from a computational point of view and considering how sensing phase of context features is performed. Pruning methodologies can be divided in two families: pre-pruning and post pruning. The pre-pruning methodology may consist in using a threshold test for identifying features that perform good results in the classification phase. On the other hand, post-pruning techniques consist in using a validation set for the reduction of the length of trees.

The importance of using decision trees in processing big data resides in the ability to manage large amount of data, step by step reducing the amount of information to be taken into account. On the other hand, in many applications what may be a bottleneck is the definition of numerical thresholds, considering numeric features. While in many decision trees algorithms this phase is delegated to the algorithm itself, a very important speedup can be obtained in programmatically dividing numerical features in different ranges.

Another aspect to be taken into account when considering decision trees methodology is the management of single features and of aggregated ones. This aspect is quite similar the difference between primary and secondary context, in which secondary context always derives from primary context features. The ability to manage representation of context both for primary and secondary context, allows decision trees to be taken into account as a valid solution for context modeling. This conceptualization emerges, for example, while considering the FICUS classification algorithm [63].

Following this logic, many solutions have been adopted, but it has been demonstrated that it does not exist a single methodology and discriminant metric that can be applied to all the application scenarios [61]. On the other hand, as previously shown in the previous chapters, the adoption of decision trees in context aware systems has seen very promising results achieved.

7.2 ID3

In context aware systems, representation on knowledge is a key factor both for computational reasons and for manage large sets of data. Moreover, providing automated mechanisms to understand underlying logic of a process, using contextual features, easy the development of context aware systems. A great boost to this research field has been gained by decision trees, that have their roots in machine learning field. A well known statement, provided in [64] define three principal features related to machine learning, that can be summarized in:

- the underlying learning strategies used;
- the representation of knowledge acquired by the system;
- the application domain of the system.

Using this set of feature, it is possible to match the strength of decisions trees in the development of context aware systems. In fact, while considering "the underlying learning strategies used" in decision tree, it is easy to map discriminant metrics, related to sampled features, to the need of context aware systems (especially in dynamic contextualization) to understand relevant features. Moreover, "the representation of knowledge acquired by the system" indicates that the potentiality of decision trees applications to context awareness, can be related not only at a hidden computation level, but also can be extended to the human interaction with the proposed system. Indeed, the ability of decision trees, to be well readable and meant by humans, easy the way in which the management of a context aware system can be controlled in its execution. Automatic definition of rules is not always seen as a best practice, because it does not exist a generalized and easy way to represent rules. On the other hand, trees can be well understood in the execution of automated tasks. At last, "the application domain of the system" should be more and more general, while considering automated mechanisms to provide context modeling and context reasoning. Most of machine learning approaches need specific application domain, while, decision trees, can provide sufficient performances in general purpose applications. How much decision trees applications can vary, can be seen in previous chapters. Many context aware applications have been developed, using decision trees, going from the diagnosis of medical condition, using symptoms as context features, to flowers classification, using biologically features of plants.

One of the simplest decision tree algorithm developed in literature is the Concept Learning System framework (CLS) [65], in which the main rule in building the classification tree resides in minimizing the "cost" in the classification phase related to an object. What attributes have to be selected during the construction of the tree are delegated to the designer of the tree. On the other hand, the most interesting thing in the ID3 algorithm, resides in choosing attributes using a pre-defined metric. The main evolution of the ID3 algorithm is the automatic selection of attributes during the building phase of the decision tree.

Considering a set S of samples sensed, it is important to introduce the information entropy of the total set of samples. It is defined as:

$$Entropy(S) = -\sum_{c \in C} p(c) \log_2 p(c) \tag{7.1}$$

where, $p(c)$ is equal to the number of samples of class c divided by the total amount of samples.

During the construction phase of the classification tree, the S set will be considered specifically, considering pre-chosen features from the training set. The intuition of Quinlan in formalizing the ID3 algorithm resides in the definition of information gain, related to a specific attribute. The main question in this approach is: what is the knowledge that is driven by a specific attribute? What is the difference between considering one attribute in the building phase, instead of another one? The information gain tries to answer to this questions, considering the difference between the information entropy of a system and the entropy related to a specific attribute:

$$Information\ Gain(A, S) = Entropy(S) - \sum_{t \in T} p(t) Entropy(t) \tag{7.2}$$

In this equation the amount of entropy, related to a specific attribute A is calculated as the sum of all the entropies, considering a specific value of the considered attribute. This value is multiplied with the proportion between the total amount of samples t and the entire set S.

This represent an important improvements in the building phase of decision trees, because it takes into account the weight of an attribute in the decision phase, using a specific and deterministic metric.

7.3 C4.5

The limitations of the ID3 algorithm mostly resides in managing attributes with a lot of values. Indeed, consider an attribute with a huge amount of values implies that it will have a greater information gain.

The evolution of the C4.5 [66], compared to the ID3 algorithm, is in compensating the number of values of each attribute, in the splitting criteria. Indeed, in C4.5 it has been defined the Potential Information as:

$$Potential\ Information(A, S) = -\sum_{t \in T} p(t) log_2 p(t) \tag{7.3}$$

Following this criteria, how an attribute is chosen for the creation of the tree, follows a maximization of the Gain Ratio, defined as:

$$Gain\ Ratio = \frac{Information\ Gain}{Potential\ Information} \tag{7.4}$$

Moreover, another enhancement of the C4.5 is in considering both discrete and continuous attributes in the construction of the decision tree. This is surely useful in context aware applications.

CHAPTER

EIGHT

ATTRIBUTES SELECTION AND DYNAMIC CONTEXTUALIZATION

8.1 Features Setting for Context Modeling

Environmental and user features are generally considered as context when they are able to characterize the situation of an entity. This approach has been formally defined in [67], in which authors state that:

> *any information that can be used to characterize the situation of an entity, where an entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and the application themselves.*

This definition is very useful to focus the general problem of considering a restricted set of features, belonging to an environment, to be meant as context. On the other hand, features that may be considered as context, would not be useful for the representation of a context model. For example, environmental and users' features, that might be considered as context, for their role in the process to be modeled, might be useless in the representation of it. Moreover, state of the art definition, provided by Dey [67] underly and restrict what context might be in stating that:

> *Context is typically the location, identity and state of people, groups, and computational and physical objects.*

This kind of boundaries don't allow to solve context definition of a large set of feature, but it is closer to what context aware application are meant to do: solve users' issues. The restriction to a subset of features is quite closer to what generally and intuitively humans think context is, but it might be distant to each specific context aware goal to be reached.

For this reason, a more comprehensive definition of context has been given by Winograd in [24], in which author distinguishes two concept, settings and context, focusing on how a feature characterizes its role in communication. In this way Winograd links more deeply context definition to context representation (and possibly reasoning):

> *Context is an operational term: something is context because of the way it is used in interpretation, not due to its inherent properties.*

The distinction between these concepts is very useful for understanding dynamic contextualization, because it clarifies how to filter available datas in context aware systems. In the next paragraphs it will be explained how dynamic contextualization can overcome traditional context modeling, using perspectives, so that the settings can automatically generate specific context models in different situations.

8.2 Dynamic Contextualization

One of the most known issue in context aware systems is in choosing the proper set of attributes that the system has to manage. This problem has been addressed by scientific literature in many cases, especially in the definition of context. In Winograd work [24] for example, the author relates to context features as a subset of the overall attributes that are related to a specific system. He explicitly states that:

> *The user of a computer system is always situated in some setting of people, places, and things (including computers), regardless of which aspects of that setting are used as context in communication.*

This means that the most difficult task in context awareness is related to interpreting the setting and to understand relevant features to be used as context. The connection between the target to be achieved and the setting could be very difficult to be detected by humans, especially when it implies a deep knowledge of the underlying mechanism of the system.

For the reason above, in [68] it has been defined the concept of dynamic contextualization. The dynamic contextualization process is divided in four steps:

1. Representing long-term user information and knowledge about the domain and potential context factors.

2. Sensing of potentially relevant information about the user's current state.

3. Dynamically identifying contextually relevant elements.

4. Reasoning (for instance inferring recommendations) based on that context.

8.2.1 Intrinsic informations about the user

The first step of the dynamic contextualization process is the acquisition of long term user informations, as stable features that it is supposed will not change in the future. This kind of information is essential for dynamic contextualization, because it may decrease the complexity of the context aware system. Intrinsic informations management can avoid context aware systems, to adopt the most suitable strategy, considering, not only the single users' information but also community aggregated values. This means that the fast availability of intrinsic informations about users can speed up the development of complex context aware system, in which both personal datas, community aggregated data and environmental data can play a crucial role. Intrinsic informations about the user can consist in: name and surname, sex, age, birth city, buddy list, etc.

8.2.2 Situation sensing

Actual context data sensing, related to users, consists both in the management of volatile data about the situation of a user and the processing of secondary context features, considered in the acquisition phase. It means that situation sensing has to be able both to properly interact with low level sensors and smart devices and create mechanisms to understand how to easily compute context features in a reactive form. Most of the time, context feature extraction could be a difficult task to be performed. In this phase, the adoption of classification trees can better the performances of the entire context aware system and solve this kind of issues, related to the acquisition phase. Context features, associated to the situation sensing, can be generally linked to the actual location or to the temporal instant in which the user is, etc., and the kind of situation sensed features varies in relation to the application scenario. For example, in a medical scenario, situation sensing can be defined as the set of features that characterize short term features of a patient, like clinical analysis, or body sensors acquired data.

8.2.3 Dynamic identification of context

Defining the set of context features is a huge problem in context aware systems, mostly because the total amount of features to be taken into account is related to the main goal to be reached. Indeed, different application scenarios can need specific sets of context features in the same application environment. The overlapping of context sets, related to pre-defined environments, is generally solved in the design phase of a context aware system, in which who develops a context aware system has the role to choose the most suitable set of features. The identification of the proper set of features, on the other hand, most of the time, needs a deep knowledge of intrinsic logic and of how to reach a specific goal. The different perspective of how to consider context features sets is called dynamic contextualization and it has to be considered in how a specific environment has to be managed in the adoption of context streams and of user's related states. A recent implementation of the dynamic contextualization approach can be found in [68], but literature is lack of general bindings between dynamic contextualization and automated methodologies to couple how different perspectives are performed for specific applications. In this dissertation it is intended to understand how dynamic contextualization can be performed, using decision trees, to identify in an autonomous way, most relevant context features to perform context reasoning. For example, static features, related to a user and its surrounding environment, can be used both for providing a context aware system, able to guide the user to the nearest restaurant, or to allow it to buy clothes in the nearest shop. This means that context reasoning goals drive dynamic contextualization differently, and that future challenges in context awareness will be focused not only in how to perform contextualization, but also in providing a suitable way to automatically understand how to frame the goal to be solved, without the need of pre-defined sets of rules, or with pre-defined set of attributes. Considering this kind of approach, static users informations play an important role in guiding context reasoning, because they can be conceptually processed and aggregated for specific tasks to be achieved. On the other hand, static context does not differ so much from dynamic situations, because decision process can take into account static and dynamic features in different processing steps. When considering static or dynamic features is delegated to the classification algorithms and it impact only in the fetching state of them. Considered perspectives specifically define context model, that can be processed both on user's needs and on environmental conditions. This kind of approach overcomes traditional way of considering context aware systems, purely static and not automatically adaptable. Moreover, using decision trees technology, acquisition step is only restricted to needed features.

For example, considering a scenario in which static user's features, dynamic clinical values and diagnosys represent the total amount of available features, dynamic contextualization will provide filtering and automatic context reasoning, for suggesting the most suitable patient treatment.

8.2.4 Reasoning for dynamic contextualization

As stated in the previous paragraph, dynamic contextualization provides an efficient mechanism to select distinct sets of features, related to a vast range of perspectives. The main problem, related to this approach is linked to how obtain a consistent context reasoning, so that top level applications would use it. Representation of overlapping context models, is intended to be solved in this dissertation, using decision trees. In a clinical scenario, for example, different perspectives of breast cancer diagnosis can be represented as different decision trees. Moreover, dynamic contextualization will work in the decision process, adopting different branches, driven by nodes' values of the tree, as shown in Fig. 8.1.

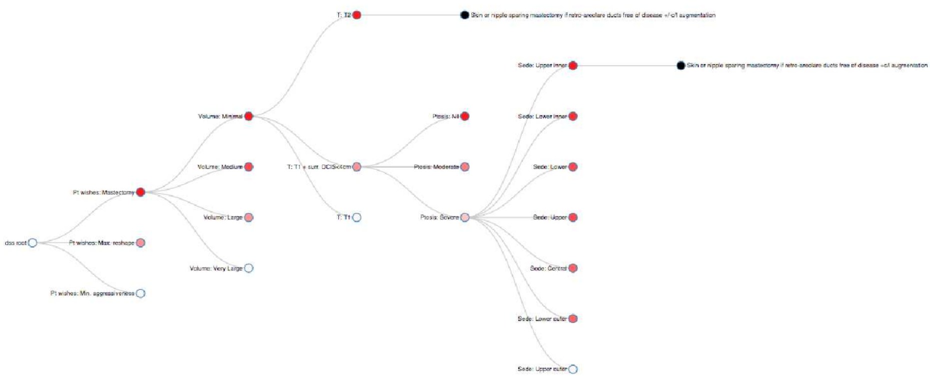

Figure 8.1: *Dynamic contextualization in patients' treatments.*

CHAPTER

NINE

FORMAL ANALYSIS OF SURGICAL DECISION MAKING

9.1 Background

Prior to the historical trials on breast conservation a mastectomy was the only surgical choice for primary treatment of breast cancer. Once the safety of glandular preservation had been established at the beginning of the 1980s, a second possible treatment could be offered to patients. [69, 70, 71, 72, 73, 74]

Initially partial mastectomies appeared to guarantee integrity, but quite soon it became clear that breast conservation in some cases may not yield satisfying results. [75, 76] Sometimes the cosmetic appearance after these operations was rather poor with visible scarring and severe deformities of the mammary shape. Several studies confirmed unsatisfactory results, even for breast conserving surgery, in up to twenty percent of cases [77, 78]. These failures initiated some reports regarding techniques derived from cosmetic surgery (breast reductions, mastopexies), to remove breast tumors without deformities. [79, 80, 81]. The advent of primary systemic therapies has also enlarged the number of possible therapeutic choices in the hands of surgeons [82, 83]. Post-mastectomy radiation therapy (PMRT), that has recently increased its indications, may also interfere with the pathway of breast reconstruction [84, 85, 86, 87, 88, 89]. This information regarding possible failures of breast conservation and good outcomes of mastectomy and reconstruction, coupled with an increase in patients awareness, has generated a very complex and multifactorial decisional pathway [90, 91, 92, 93, 94, 95, 96, 97, 98]. With this study it has been created a software tool capable of assisting patients and surgeons in making proper decisions. I tested it in a short cohort of patients related to surgeons in order to provide a preliminary validation of this instrument. It has been assessed the reproducibility of the clinical procedure, the actual applicability of the proposed decisions and the effects on post-operative residual defects.

9.2 Methods

9.2.1 Endpoints, decisional drivers, creation of subcategories of disease

In order to analyze the decision process a small group of surgeons created a set of possible endpoints of the surgical treatment of breast cancer. These were identified as: safe removal of breast cancers on negative margins, avoiding disfiguring cosmetic results, and preserving good quality of life; therefore putting the patient at the center of the decision process. It has been hypothesized that these endpoints could be addressed combining a set of decisional drivers that include morphological elements (breast shape and size), topographic aspects related to cancer location, size and stage in association with patients' preferences regarding surgical techniques as described in Table. 9.1.

It has been created four subcategories for volume according to bra

T-Stage or Multicentric disease	Location*	Volume	Ptosis	Risk of positive margins**	Pt wishes
T>2cm	Central	Minimal	Nil	High	Mastectomy
T<2cm	Upper	Medium	Moderate	Intermediate	Max. reshape
LABC	Lower	Large	Severe	Low	Min. Aggressiveness
DCIS< 4cm	Upper outer	Very Large			
MULTICENTRIC Invasive/ Extensive DCIS	Upper Inner				
	Lower outer				
	Lower inner				

Table 9.1: *List of decisional drivers*
$*$ *not assessed for LABC Multicentric/ extensive DCIS*
$**$ *not assessed for LABC Multicentric/ extensive DCIS and localized DCIS*

size. Breast ptosis was classified in three subgroups using a modification of the classification of Regnault [89]. It has also been included in the "moderate ptosis" group patients with pseudo-ptosis and glandular ptosis to reduce the number of possible combinations. The breast was subdivided in seven subunits to locate the lump. Cases for which a mastectomy was the only possible choice did not include the assessment of tumor size, location, and risk of positive margins. For patients affected by early stage invasive cancer that can be treated with breast preserving surgery it has been decided to convey also information on the risk of positive margins derived from a validated software tool named breastconservation! [99]. However a high risk of positive margins was not "per se" an indication to perform wider excisions or mastectomies. The use of this tool was valid only for patients with invasive cancer. Patients' preferences were investigated by doctors and breast care nurses during pre-op sessions using specific leaflets and multimedia tools [100]. It has been subcategorized patients' wishes according to three subcategories:

- minimal aggressiveness (i.e.: wide local excision, oncoplastic level 1, unilateral oncoplastic level 2, mastectomy without reconstruction, mastectomy and implant based reconstruction without contralateral adjustment, mastectomy and implant based reconstruction for radio-treated patients)
- maximum reshape (i.e.: bilateral oncoplastic level 2, contralateral adjustment if mastectomy is unavoidable autologous flap reconstruction for radio-treated patients)
- mastectomy (i.e.: mastectomy and implant based reconstruction, mastectomy without reconstruction for radio-treated patients)

At the end of this process it has been identified four subgroups named as: *ESBC* (localized invasive cancers with or without a minor DCIS component), *DCIS localized* (small DCIS suitable of breast conservation), *MULTICENTRIC* (early stage disease widespread in the breast, including DCIS) and *LABC* (locally advanced cancers requiring multimodality treatment including radiation). The decisional elements were combined manually in an electronic spreadsheet; each combination was considered as a single clinical case and associated to the most suitable surgical option by a panel of experienced oncoplastic surgeons. The final surgical suggestion was established according to current standard practice and to previous observation reported by [87, 93, 101, 102, 103, 104, 105, 61].

9.3 Formal analysis and design of the decision tree

The decisional process was analyzed according to the Iterative Dichotomiser 3 algorithm (ID3) with the creation of a navigable decision tree and a prototype decision support system software (DSS) tool [106, 107].

The Information Gain $IG(A, S)$ is the measure of the difference in entropy from before to after the set S is split on an attribute A. In other words, how much uncertainty in S was reduced after splitting set S on attribute A. For $IG(A, S)$ the Information Gain is:

$$IG(A, S) = H(S) - \sum_{t \in T} p(t)H(t) \tag{9.1}$$

where $H(S)$ is the entropy related to the specific subset of the considered records; T is the set of values for the specific attribute A; $H(t)$ is the entropy calculated considering the specific value t of the attribute A; $p(t)$ is the probability of choosing a record with the specific value t related to the attribute A. The Information gain, related to each attribute and to the four clinical subgroups (ESBC; DCIS localized;

MULTICENTRIC; LABC) , was calculated, taking into consideration the subtraction between the information entropy of a specific subset of records and the sum of the entropies related to each value of one single attribute. Using this method, it has been chosen iteratively the attribute that minimizes the amount of entropy of a specific subset of records as a node of the decision tree. The entropy $H(S)$ can be seen as:

$$H(S) = -\sum_{x \in X} p(x) \log_2 p(x) \tag{9.2}$$

where S is the set of the records manually edited by a group of breast cancer surgery experts; X is the set of classes and p is the probability of choosing a record that owns a specific x class.

9.4 Preliminary Clinical testing

Once the DSS was available it has been tested it on fifty-two patients to verify its clinical usability in a single unit in Catania- Ospedale Cannizzaro from November 2013 to October 2014.

First of all it has been investigated the repeatability of the suggestion produced by the DSS. It has been verified the concordance between the decision produced by an expert operator in two different times (during the last consultation and the night before the operation). Afterwards it has been compared the output obtained by a newly trained surgeon to that of an expert one. Finally it has been assessed the number of times the actual surgical decision was concordant to that suggested by the DSS (last consultation).

As a secondary endpoint it has been estimated the ability of the DSS to prevent post-breast-conserving therapy defects. Patients treated by breast conserving surgery were observed post-operatively at three months for the evaluation of residual deformities using the scale proposed by Fitoussi et al. [108]. The score of patients who followed the DSS suggestions was compared to that of those who refused the proposal of the software tool.

The medium follow-up was 12.5 months. Finally, to assess the length of the process the median number of consultation required to reach a decision using the DSS was also calculated.

9.5 Statistical Analysis

Continuous variables were expressed as mean and standard deviation and categorical variables as absolute number and percentage. Differences in patients' characteristics of patients between groups were tested by t-student and exact Pearson chi-squared test for continuous and categorical variables. Exact binomial confidence intervals were calculated for proportions. All statistical tests are two-sided and p-values$<$0.05 are regarded significant. The data are analyzed using SAS version 9.2 (SAS Inc., Cary, NC, USA).

9.6 Results

It has been developed a prototype software tool to assist surgeons in making decisions in oncoplastic surgery of the breast (figure: 9.1).

A total of 2592 combinations have been generated, subdivided respectively in: 2268 for the group "ESBC"; 252 for the "localized DCIS" group; 36 for the "MULTICENTRIC" group and 36 for the "LABC" group. In the group "ESBC" the operator may also input data regarding the risk of positive margins. The total number of final suggestions was 97. The decision trees obtained are visible in figures 9.2, 9.3, 9.4, 9.5. A navigable version was also produced (demo visible at link http://raefin.com/oncoplastic_decision_tree/.). The estimate of the information gain calculated on the four databases demonstrated that patients' wishes are the root of the decisional tree in all the subgroups created (Tab. 9.2). The baseline characteristics of the

ESBC		**Localized DCIS**	
T	GAIN= 0.85	T	GAIN= 0.62
Location	GAIN= 0.75	Location	GAIN= 0.55
Volume	GAIN= 0.99	Volume	GAIN= 0.79
Ptosis	GAIN= 0.36	Ptosis	GAIN= 0.21
Risk of margin+	GAIN= 0.03	**Pt wishes**	**GAIN=1.09**
Pt wishes	**GAIN= 1.18**		
LABC		**Ext DCIS**	
T	GAIN= 0.91	T	GAIN= 0.91
Volume	GAIN= 1.00	Volume	GAIN= 0.89
Ptosis	GAIN= 0.45	Ptosis	GAIN= 0.23
T	GAIN= 0.91	T	GAIN= 0.91
Pt wishes	**GAIN= 1.29**	**Pt wishes**	**GAIN= 1.00**

Table 9.2: *Values of information gain according to each clinical subgroup*

population are described in (Tab. 9.3).

Patients wishing a minimally aggressive surgical approach were 59.6%. A smaller proportion of the sample (19.2%) belonged to the group whose surgical preference was indicated as "mastectomy". A median of 3 sessions was necessary to reach a surgical decision using the DSS.

The re-testing by the same expert operator showed an observed concordance (OC) of 0.98 (0.90 to 0.99; 95% C.I.) and the comparison between the first test by an expert operator and the test performed by a second surgeon the OC value was 0.88 (0.77 to 0.96; 95% C.I.). The OC between the actual decision and the decision suggested by the DSS was estimated for a value of 0.69 (95% C.I. 0.55-0.81). The suggested decision was not followed by a correspondent actual decision

T- Stage or Multi-centric disease	N=52 (%)	**Location**	N=42 (%)
T>2cm	3 (5.8)	Central	3
T<2cm	37 (71.2)	Upper	14 (26.9)
LABC	2 (3.8)	Lower	4 (7.7)
DCIS<4cm	2 (3.8)	Upper outer	9 (15.4)
MULTI-CENTRIC Inv/Ext DCIS	8 (15.4)	Upper Inner	6 (11.5)
		Lower outer	5 (9.6)
		Lower inner	1 (1.9)

Table 9.3: *Distribution of decisional drivers among population: T- Stage or Multi- centric disease and Location*

Volume	N=52 (%)	**Ptosis**	N=52 (%)
Minimal	10 (19.2)	Nil	14 (26.9)
Medium	16 (30.8)	Moderate	18 (34.6)
Large	21 (40.4)	Severe	20 (38.5)
Very Large	5 (9.6)		

Table 9.4: *Distribution of decisional drivers among population: Volume and Ptosis*

Risk of margin+	N=40 (%)	**Pt wishes**	N=52 (%)
High	25 (48.1)	Mastectomy	31 (59.6)
Intermediate	6 (11.5)	Max. reshape	11 (21.2)
Low	8 (15.4)	Min. Aggressiveness	10 (19.2)

Table 9.5: *Distribution of decisional drivers among population: Risk of margin+ and Pt wishes*

Comparison	**Observed concordance (95 % C.I.)**
Expert user (Assessment 1) vs. Expert user (Assessment 2)	0.98 (0.90 to 1.00)
Expert user (Assessment 1) vs. Non Expert User A	0.88 (0.77 to 0.96)
Expert user (Assessment 1) vs. Actual Decision	0.69 (0.55 to 0.81)

Table 9.6: *Concordance analysis*

in a total of 14 cases (Tab. 9.6).

Twenty (37.3%) wide local excisions (with or without any kind of nipple areola complex repositioning) have been performed, 13 (24.5%) therapeutic mammoplasties (of which 8 unilateral), 14 (26.4%) skin or nipple sparing mastectomies and immediate reconstruction, 1 (1.8%) radical mastectomy without reconstruction and 2 (3.7%) radical mastectomies with delayed reconstruction. Three (5.6%) patients underwent neo-adjuvant chemotherapy before surgery.

The incidence of post breast conservation residual defects was investigated in this series. Twenty-nine patients (87.7%) were reported as type I and II of the classification of Fitoussi. Four patients (12.1%)

Classification of Fitoussi	**N (%)**
Type I/II	29 (87.7)
Type III	4 (12.1)

Table 9.7: *Incidence of post breast conservation defects according to Fitoussi.*

	Concordance (N=21)%	No concordance (N=12)%	P-value
Classification of Fitoussi			0.004
Grade I	19 (90.4)	5 (41.6)	
Grade II	2 (9.5)	3 (25.0)	
Grade III	0	4 (33.3)	

Table 9.8: *Incidence of post breast conservation defects according to Fitoussi.*

were classified as type III. (Tab. 9.7).

It has been found that all patients with severe deformities (type III) were belonging to the ”no concordance” subgroup (4 patients 33.3% vs. 0; p=0.004) (Tab. reftable:breast6).

Women who did not follow the suggestions of the DSS were older, with lumps located in the upper-inner quadrant, between the superior quadrants of the breast, or in the lower outer quadrant. They also had small or very large breast more frequently (respectively 25% vs. 0 and 16.6 % vs. 9.5%, p=0.04) and a lower risk of positive margins with breast conservation (91.6% vs. 57.1 p=0.04). (Tab. 9.9)

All patients with type III defects were older than 75. Three patients (9.0%) advised to undergo a mastectomy by the DSS indicated their preference for breast conserving surgery and retained an accept-

	Concordance (N=21)	**No concordance (N=12)**	**P-value**
Age years, mean (SD)	64.58 (15.8)	51.1 (13.0)	**0.004**
Extent of disease			**0.206**
DCIS<4cm	3 (14.2)	0	
T<2cm	18 (85.7)	12(100%)	
T>2cm	0		
Breast Location			**0.009**
Central	1(4.7)	0	
Upper Outer	8 (38.0)	0	
Upper Inner	0	3 (25.0)	
Upper	7(33.3)	5 (41.6)	
Lower outer	1 (4.7)	4 (28.5)	
Lower inner	1 (4.7)	0	
Lower	3 (14.2)	0	
Breast Volume			**0.04**
SMALL	0	3(25)	
MEDIUM	8(38.0)	1(8.3)	
LARGE	11 (52.3)	6(50.0)	
VERY LARGE	2(9.5)	2 (16.6)	

Table 9.9: *Incidence of decisional drivers among patients who followed the DSS suggestion (concordance)and those who did not (no concordance).*

Ptosis			**0.2**
NO PTOSIS	2 (9.52)	1(8.33)	
MODERATE	11 (52.3)	9(75.0)	
SEVERE	8(38.0)	2(16.6)	
Risk of positive margins			**0.044**
LOW	12 (57.1)	11(91.6)	
INTERMEDIATE	3(14.2)	1 (8.3)	
HIGH	3(14.2)	0	
N/A	3(14.2)	0	
Patient's wishes			**0.18**
MASTECTOMY	0	0	
MAX RESHAPING	5(23.8)	0	
MIN AGGRESSIVENESS	16 (76.1)	12(100)	

Table 9.10: *Incidence of decisional drivers among patients who followed the DSS suggestion (concordance)and those who did not (no concordance).*

able breast shape. Finally, 8 (24.2%) patients who indicated a minimal aggressive approach were recommended to undergo a unilateral breast reduction that they refused to undergo an even simpler wide local excision. Three of them reported a distortion of the final breast shape.

9.7 Discussion

The increased complexity of the decisional process in breast cancer surgery is well documented [109, 110, 111, 112, 113]. Several studies have tried to overcome this condition proposing algorithms, flow charts and nomograms to support the final decision regarding surgical treatment [114, 115, 116, 109, 110, 90].

In 2012 Clough et al. [109] proposed a quadrant-per-quadrant approach to oncoplastic techniques for breast cancer that tailored the mammoplasty to each tumor location. A nomogram was proposed to select the correct technique according to each quadrant but considerations regarding breast shape and size were not included. No suggestions were provided for tumors located in the central quadrant. This study followed a previous one by the same author. Even in this case considerations on breast shape and volume were missing.

Munhoz et al [116] proposed an algorithm based on breast size in relation to tumor location and extension of resection. The authors tested it on 206 patients claiming that complications were similar to those reported in other clinical series. Subjective or objective evaluation of final results was not assessed. The increased complexity produced by adding the volume estimates is clearly visible in the diagrams displayed which are less readable compared to the those proposed by Klough.

Kronowitz et al. [115] presented a management algorithm for repairing partial mastectomy defects based on some clinically relevant parameters including timing of reconstruction in relation to radiation therapy, status of the tumor margin, extent of breast skin resection, breast size, and whether the cosmetic outcome would be better after a total mastectomy with immediate breast reconstruction. The study is not associated to any clinical validation and the flow chart presented is very complex. Notably the authors used a formally correct graphic language.

Other flow-charts and diagrams have been used in the recent times also to assist decisions in the field of mastectomy and reconstruction especially when post-mastectomy radiotherapy (PMRT) is required [90, 117].

Many other examples of flow charts, decision makings and algorithms can be identified. Most of these lack validation and may be considered mere experts' opinions; the large majority of them are strictly oriented to specific clinical conditions (PMRT, Oncoplastic surgery etc.). None of them include a formal analysis of the process or the integration of patients' wishes in the decision process.

Moreover, context aware systems have been conceptually successfully applied to the clinical decision process. Most of the proposed solutions are strictly related to decision support system development. More deeply, ubiquitous computing has been developed for taking care both of patients and physicians interaction [118] or for providing patients charts on mobile [119]. A human to machine interaction approach has been also developed in [120], more focused on how smart devices have to interact with the environment and patient's behavior.

In this study, most of the limitations of previous experiences have been overcome. First of all it has been extended the pathway to the largest possible combination of cases in order to get an omni-comprehensive view of the surgical treatment. It has been associated most of the decisional drivers proposed by older studies, including estimates of breast volume and ptosis, and the location of the lesion, and of the amount of tissue to be removed. Notably, it has been added to these elements an evaluation of patients' preferences regarding the surgical approach. Considering the state of the art, this is the first time that such appraisal has been integrated into a surgical decisional pathway. The combination of all these elements created a very complex twist, poorly manageable in clinical practice. Thus, the main output of this study is the creation of a decision support system software tool (DSS) in which all the drivers can be combined electronically to generate a surgical suggestion. Beside this system it has been also created a navigable decision tree that allows surgeons with lesser experience to search throughout all the possible combinations to raise their knowledge. The design of the decision trees was also independently analyzed confirming that it has been assigned the highest weight to patients' preferences. The intricacy of the whole system is visible in figures 9.2, 9.3, 9.4, 9.5 and it resembles the graphic style of a genome (figure: 9.1). It has been used this system on a small cohort of randomly assigned patients who underwent surgery from a single oncoplastic surgeon. The median number of consultations was quite high and it may be supposed that it could be even higher as some of the patients had already had a positive imaging and core biopsy at the time of the first consultation. Certainly the central role of the patient and the increased awareness of the process had an impact on this. However the patients centered approach demonstrated its unneglectable role in improving the outcome of the oncological treatment several times [121, 122, 123, 94] With this test it has been investigated the reproducibility of the procedure in the hands of an expert operator and in that of a second newly trained surgeon. It has been confirmed a good concordance both when the DSS is used by an expert in two different sessions, and when the output of the experienced operator is compared to that of the newly trained one. To better understand the value of the DSS it has also been assessed the concordance between the actual surgical decision and that suggested by the system. Not surprisingly this value was quite low. Specifically it has been noted that four patients candidated by the DSS for some kind of minimal breast reshape refused it and underwent a standard wide local excision. This of course generated a distortion in the post-operative appearance of their breast (classified as grade III according to Fitoussi). Interestingly all these patients were older than 75 and had associated comorbidities. This trend may indicate the need of adding other drivers to the DSS (such as age and comorbidities) and a fourth subcategory of patients wishing an ultra-minimal surgical approach. Among patients who refused the suggestion of the DSS it has also been shown three cases advised to undergo a nipple sparing mastectomy and reconstruction for a poor breast to tumor ratio. They preferred to undergo a wide local excision and despite the difficult position of the cancer the final results did not produce any major deformity. It can be shown that the suggestion to undergo a mastectomy is due to the original conception of the framework which predated the publication of convincing evidences regarding the usefulness of leaving wide resection margins after breast conservation for invasive cancers [124, 125]. In view of these findings and by the time experience in the field will increase, any revision the framework will be considered.

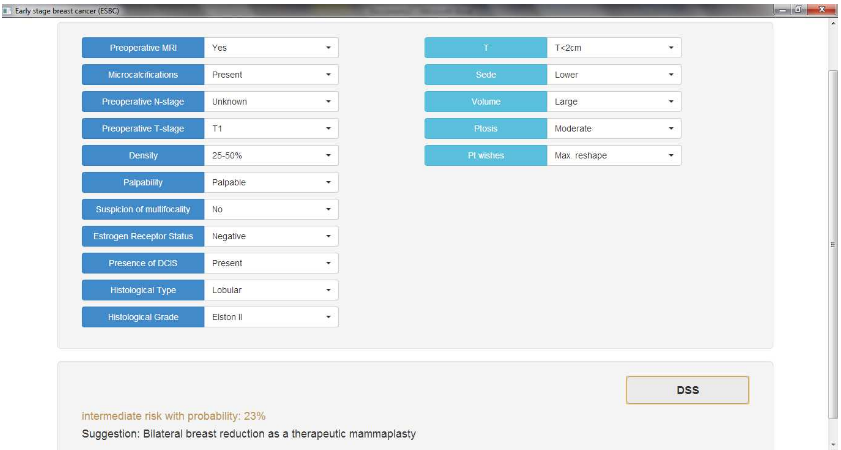

Figure 9.1: *Outcome of the DSS*

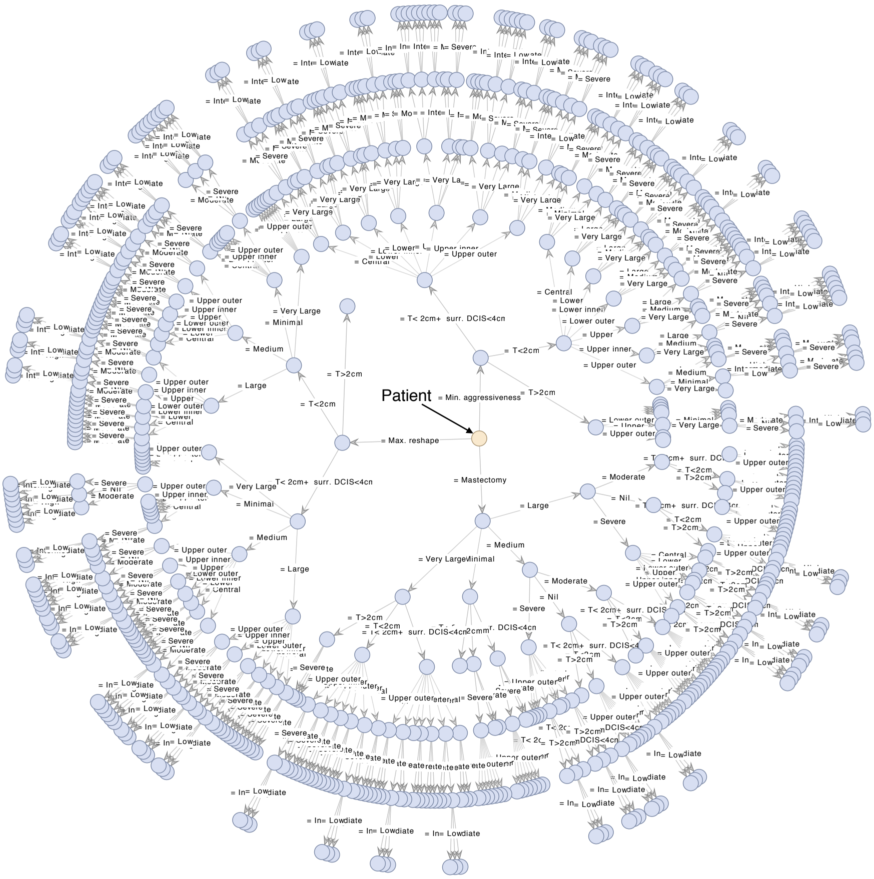

Figure 9.2: *Decision tree for ESBC*

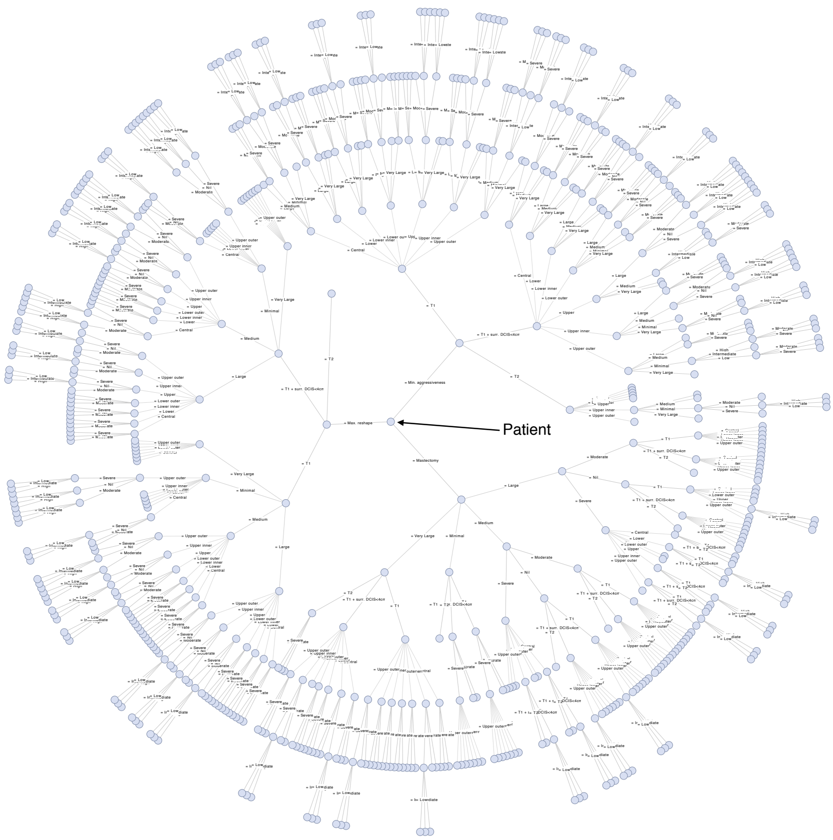

Figure 9.3: *Decision tree for localized DCIS*

Figure 9.4: *Decision tree for MULTICENTRIC*

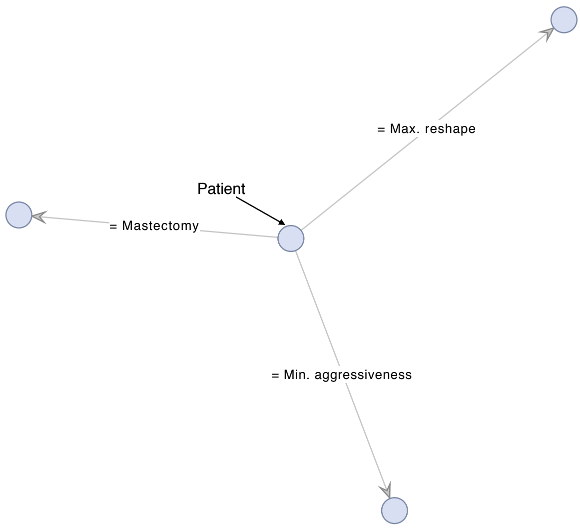

Figure 9.5: *Decision tree for LABC*

CHAPTER

TEN

CONCLUSIONS

The dissertation presents how context awareness can be applied both to the machine to machine paradigma and to manage human to machine interactions. The Internet of Things is still rapidly growing, populating the environment with a huge amount of smart devices. "Things" now are able to extend the concept of the wireless sensor networks paradigma to new applications, that could not be imagined just a decade ago. The missing chain to the ubiquitous computing scenario can be identified in this new swarm of intelligent devices, that can act, according to programmable logic inside micro-controllers or in the cloud, to reach the final goal of enhancing the quality of human life. Moreover, what emerges from the research work is that the role of smart devices in current technology has been changing, pushing some of the agent modeling techniques to the Internet of Things scenario. "Things" are not yet purely meant as objects, able to sense and execute commands, but begin to act in a new way, following human behavior.

The increasing computational power, communication capabilities and battery storage of smart devices drive a new revolution in cooperative systems, in which context awareness concepts can be applied as in the human to machine paradigma. Concept like self-awareness and trustability can now be related to "things" too.

During the research work, it has been studied how to apply context aware to the machine to machine interaction, trying to keep new results and drawbacks of this kind of application. It is intended to follow up the research in this field, to better proposed results, and to find out new strategies to be taken into account in machine to machine context awareness.

On the other hand, the opportunities offered by the increasing number of devices interconnected among them, has to deal with what the technology is for humans. The unconscious way in which we usually turn on the light, or in which we use a pen to write a letter, is going to be the same in current human to machine interaction. This new perspective is actually driven by context aware systems that clarify most of the issues related to the development of such kind of solutions. What has been found, during the research path, is that usually context awareness did not evolve from the original definitions. The missing step in the context awareness ecosystem has been to find out a valid methodology to uncouple developers' choices from the selection of relevant environment features (to be considered in a context aware system). The analysis on how decision trees' building work, was fundamental to understand logical connections between dynamic contextualization and the splitting rules, used to identify relevant features in sets of data. The results have shown how it is possible to connect smart devices to a dynamic context aware system, to provide surgical suggestions and practical usage of the system to give a new representation of the phenomena to final users, without taking into account intrinsic technological meaning of the formal analysis tool.

These results open the way to future works that will extend decision trees study for developing new applications in other research fields, more and more influenced by context aware systems.

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