Specknets: A Case Study for Artificial Immune Systems

by

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A thesis submitted in partial fulfilment of the requirements of

Edinburgh Napier University,

for the award of Doctor of Philosophy

School of Computing

April 2012

Abstract

This thesis examines the role of wireless sensor networks, as illustrated by specknets, as an appropriate platform for developing novel immune-inspired algorithms. Properties of the immune system and wireless sensor networks are examined in parallel, revealing a potential mapping between the two. The cognitive view of the immune system is identified as appropriate for further investigation at the theoretical level, while the functionality of dendritic cells becomes the focus in terms of biology. An agent-based model is developed as an exercise in understanding the dendritic cell function, emphasising the aspect of mobility. The model is then developed into a simulated implementation for specknets, using the application problem of temperature monitoring and control. The thesis concludes with an analysis about certain aspects the immune system and the specknet, and the proposal of a methodology to allow blending of ideas derived from two such complex systems.

Acknowledgements

Preparing this thesis for submission is one of the hardest things I ever did. It would not have been possible without a number of people. First, Emma Hart, my supervisor, who somehow manages to achieve progress out of chaos and make sense out of my confusion. Ben Paechter's help came into small doses with tremendous impact. Alex Young provided invaluable support in place of a technical advisor. I thank you all.

At the backstage, the following people also played an important role throughout my endeavour in their own way. Jon Kerridge; this thesis is a testament to persistence prevailing over glass-half-empty thinking. Jon Timmis; I was a tad late, but here is finally an answer to your question from ICARIS 2007. Mark Neal; for refusing to conform. Alex Freitas; for his kind support. Jon Oberlander; for his advice on how to write my thesis which was "First, define expectations."

P.S. To anyone undertaking research studies, make sure to read [19].

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Abbreviations

AAIS applied artificial immune system

ABM agent-based model

ACU air conditioning unit

AIS artificial immune system

APC antigen-presenting cell

CIS cognitive immune system

CSMA carrier sense multiple access

DC dendritic cell

DCA dendritic cell algorithm

GPS global positioning system

ICARIS international conference on artificial immune systems

MAC medium access control

MANET mobile ad hoc network

MHC major histocompatibility complex

OSI open systems interconnection

pDC plasmacytoid dendritic cell

PLT primary lymphoid tissue

RMSE root mean square error

SLO secondary lymphoid organ

TTL time-to-live

UID unique identification

WSAN wireless sensor and actor/actuator network

WSN wireless sensor network

Chapter 1

Introduction

Biological systems and processes such as the brain, evolution, ant colonies and the immune system, have resulted in computational paradigms of neural networks, evolutionary algorithms, ant colony optimisation, and artificial immune systems (AISs). Of these fields, AISs is the youngest and perhaps the most challenging in that the underlying biology of the immune system is less well understood compared, for example, to evolution or ant colonies where there is general agreement on the fundamental principles amongst biologists.

The immune system offers a great range of computationally interesting functionality and properties. Theoretical immunology provides diverse interpretations of the underlying biological mechanisms. Yet, a large body of the AIS literature tends to focus on a limited number of immunological aspects, theories and models. Furthermore, major existing AIS application domains, such as clustering/classification, computer security, optimisation, tend to mimic those used by evolutionary computing and machine learning practitioners, thereby potentially missing opportunities to exploit the rich underlying complexity of the immune system in novel application areas.

In computing, advancements in miniaturisation continually push the boundaries of engineering smaller computational devices, leading to development of new technologies such as wireless sensor networks (WSNs). WSNs are envisioned to provide a wide range of services, from remote monitoring of physiological data about patients by doctors to environmental monitoring and detection of chemical agents and pollutants in agriculture and forestry.

Research drives forward advances in the area of WSNs, however, there is still some distance to be covered for the original goals to be fulfilled. These technologies pose unique computational challenges which require further research to resolve. A *specknet* is a particular type of WSN, still in its infancy. Specknets are envisioned to be miniaturised programmable computational networks, both supporting and enabling the goal of ubiquitous computing in the future [143].

This thesis attempts to draw together the two areas of AISs and WSNs in a parallel study, in order to examine whether currently unexplored aspects of the immune system can be exploited in a challenging environment from engineering.

1.1 Aim and Research Questions

In [61], Hart and Timmis reflect on the progress the research area of AISs has made in the recent past. The authors claim that although the main application areas within which AIS techniques have been employed, specifically learning, anomaly detection and optimisation, have helped yield successful results, they have nonetheless failed to lead to carving out a niche for the field of AISs. According to [61], the reasons for this situation revolve around the fact that the aforementioned research directions fall short of exploiting the full potential of the immunological paradigm. Furthermore, the use of AIS in these applications has not been unique, in that it has not offered distinctive solutions to the problems selected for application.

As a way forward, the authors of [61] suggest a list of features the future AIS applications should have in order to meet the above challenges. These features include: being embodied; exhibiting homeostasis; encapsulating models of interactions between innate and adaptive immune components; consisting of multiple, heterogeneous interacting, communicating components; having components that can be distributed; and, requiring to perform life-long learning.

Following [61], Timmis et al. [129] express the need for a step change in the development of AISs using a principled engineering approach. The proposed approach involves the development of a new field of study, called immuno-engineering. Immuno-engineering is described as a field of interdisciplinary nature, intended to bring together experimental immunology and engineering, and to help AISs meet their true potential as a biologically inspired paradigm.

In order to develop this new field, the authors of [129] propose that a combination of principled abstraction of bio-inspired algorithms from the immune system and their testing on a number of selected case studies is required. With respect to the latter, the authors suggest that, if carefully selected, these case studies could provide a wide range of future applications for AISs. The ideal profile for such cases studies is described to exhibit a diverse spectrum of engineering features, dynamic characteristics, life-long learning and a range of space and time scales.

Taking up the proposals by Hart and Timmis [61] and Timmis et al. [129], this thesis examines WSNs as a candidate application area for AISs, based on the premise that the kind of properties they display offer a fitting match for the desirable features suggested in [61] and [129]. This assumption is explored in detail in chapter 4, having discussed the characteristics of WSNs in the preceding chapter. In brief, WSNs are made up of groups of individual elements that are interconnected at various levels and physically laid out over an area. The operation of a WSN relies heavily on interactions between these elements, with communication being a feature of vital importance to the system. In addition, many of the

application problems related to WSN environments include requirements similar to the suggested principles of embodiment, homeostasis, and life-long learning.

Besides the assumed match between the properties of WSNs and the proposed list of desirable features for future AIS applications, WSNs are an interesting application domain in their own right. A wide range of uses have been suggested for this pervasive networking technology, from environmental monitoring to health applications. As such, an additional aim for this thesis is to investigate whether WSNs provide a suitable platform which enables the development of new AIS algorithms that exploit novel computational properties of the immune system, that is, those that distinguish immune computation paradigm from other paradigms, biologically inspired or otherwise.

To summarise, the research questions examined by this thesis are:

- How far can one push the immune metaphor within the environment of a wireless sensor network, so as to achieve both exploitation of novel immune properties and develop solutions that meet the requirements of the engineered system?
- To what extent does a complex engineered system such as a wireless sensor network offer a suitable platform for developing algorithms which exploit novel computational features of the immune system?
- Can a principled methodology be developed which enables blending of ideas derived from two complex systems, a biological one and an engineered one, and if so, what stages would it involve?

1.2 Scope

This thesis is centred around the field of AISs standing between two different domains from biology and engineering, see figure 1.1. It is concerned with the place of AISs in relation to the immune system as the source of inspiration and WSNs

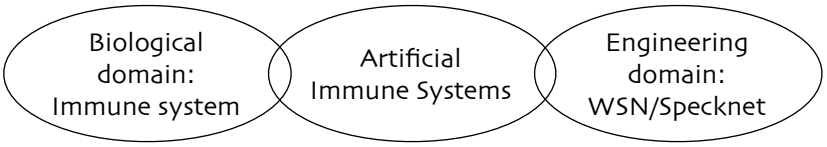


FIGURE 1.1: This thesis is centred around the field of AISs, studying its place in relation to the immune system as the source of inspiration and WSNs as a platform for AIS development.

as a platform for AIS development. Specifically, the subject of this thesis is the *process* of transferring knowledge from immunology to be applied to engineered systems within the context of AISs, using as a case study specknets in simulation.

Following from that, this thesis investigates how much potential the WSN field holds to become a promising application area for AISs. In particular, a key question of interest is how does one go about identifying novel aspects of the immune paradigm that have not been examined from a computational perspective? To explore this subject, work from the immunological literature, both theoretical and biological, is examined. An exercise in modelling high-level biological functionality is carried out, and the resulting model is transferred within the specknet environment and applied to a monitoring problem.

Throughout the investigation, no specific WSN application problems are targeted, that is no attempt is made to provide a complete immune-inspired solution either by using off-the-shelf AIS algorithms and/or developing an accomplished novel algorithm for solving a particular problem. The focus is, instead, on identifying novel computational properties and examining how these can be transferred to an engineering context. As such, although no comparison is performed between the output immune-inspired method versus classic approaches from engineering, the process of obtaining the output method leads to the proposal of a principled methodology. With this methodology the boundaries of the field of AISs are reassessed in relation to biology and engineering.

1.3 Contributions

This section summarises the contributions of this thesis in three parts.

Firstly, below are listed the contributions concerning the study of the immune system *alongside* an engineered system:

- A research framework for exploiting AISs within an application system, where the immune system is studied from a *system-oriented perspective* rather than problem-specific, a step that was missing in the majority of previous AIS research (chapter 4).
- Formalisation of an approach for identifying appropriate immune functions, principles and models for potential application, wherein adopting a *theoretical context* as part of the immune-inspired investigation for computation is vital (chapters 2 and 4).
- Formalisation of a process for studying immune function by AIS practitioners, by introducing example *dimensions* to consider when examining the immune system at the biological level (chapter 5).

Secondly, the contributions with respect to the specific subjects of focus in the domains of application and biology are:

- The first in-depth *mapping* of immunological properties and functionality to wireless sensor networks (chapters 4 and 6).
- Novel exploitation in an application of *mobility*, a fundamental property of immune cells, specifically by focussing on the migratory functionality of dendritic cells. (chapters 5 and 6).
- Development of a data collection response method within a specknet environment based on the function of dendritic cells (chapter 6).

Last, in terms of methodology:

- A principled methodology for studying in parallel two complex systems from biology and engineering (chapter 7).

Publications that have resulted from the research in this thesis are listed in appendix A.

1.4 Guide to Reading Thesis

This thesis is organised in the following chapters:

Chapter 2 overviews the immune system from a computational and networked perspective, reviews a number of dominant immunological theories and examines their impact on the field of AIS, and critiques the approach of the AIS community to immunological inspiration. Thereafter, the existing research literature in AISs and WSNs is reviewed, classified by application area and immunological theory. The chapter ends with a discussion on methodological approaches to developing AISs and identifies agent-based modelling as an appropriate technique for use in this thesis.

Chapter 3 introduces WSNs and specknets in detail and discusses the research challenges involved with such engineered systems. This is followed by introducing a map for researching and a framework for studying specknets. The chapter ends with explaining a number of networking services that are used later on in the thesis.

Chapter 4 starts with introducing the methodology followed in this thesis. It, then, continues with presenting the initial steps taken and their results. These include a study in the analogies between the specknet and the immune system, identification of Cohen's cognitive paradigm as the theoretical context for exploring the immune system further within the system-oriented context of specknets, and establishing the focus of this thesis with respect to immunobiology on the dendritic cell.

Chapter 5 deals with the dendritic cell in two parts. Firstly, the relevant immunological literature is explored to gain insight into the behaviour of the dendritic cell. Secondly, an agent-based model is developed in attempt to capture key aspects of the cell's life cycle identified earlier. The chapter finishes with a discussion that reflects on the use of dendritic cells in AISs.

Chapter 6 investigates the process of developing a novel AIS by directly including the specknet in the process. The process includes examining mapping options between the model of DC function from the previous chapter to the specknet environment, implementing the resulting AIS method in simulation, applying it to a temperature monitoring and control problem and testing its performance. The chapter ends with assessing the extent to which the approach followed facilitates exploration of novel AISs.

Chapter 7 provides an analysis on issues concerning a number of systemic aspects of the immune system and the specknet, evaluates the research questions based on evidence provided from the work undertaken in this thesis, and concludes with suggestions for future work.

Chapter 2

The Immune System and Artificial Immune Systems

2.1 Introduction

This chapter starts with an overview of the immune system in section 2.2, presenting in 2.2.1 the computational view held by the AIS field, followed by Orosz's, uncommon among immunologists, networked view in section 2.2.2. Section 2.3 discusses immunological theories. In particular, the dominant theories in the field of immunology are reviewed in 2.3.1, their impact on the field of AISs is examined in 2.3.2, and lastly in 2.3.3 the approach of the AIS community to immunological inspiration is critiqued. Section 2.4 contains a literature review on the combined areas of AISs and WSNs, organised by application areas and immunological theories involved. Finally, section 2.5 covers the subject of methodology for AIS research, examining existing approaches in 2.5.1, reviewing representative work from the AIS literature in 2.5.2 and closing with a discussion on modelling within AISs in 2.5.3.

2.2 An Overview of the Immune System

2.2.1 Computational View

The immune system has been appealing to computer engineers, like other biological systems have been in the past, as a source of inspiration for developing solutions that are based on observed natural processes to problems related to computational and engineered systems. From a computational point of view, the immune system is considered to exhibit remarkable qualities which make the immune metaphor an interesting approach to adopt within biologically inspired computing. According to the AIS literature [34, 38, 119, 127], such computationally interesting immune features include the following:

Multi-layered The architecture of the immune system incorporates several layers of different mechanisms and processes, none of which seems to play a dominant role in the operation of the overall system. On the contrary, all existing layers are important, and available to take action at any time depending on the problem present. Figure 2.1 illustrates the multi-layered organisation of the immune system, reproduced from [38], which comprises: physical barriers that block most pathogens, such as the skin and the mucous membranes; biochemical barriers which present a more hostile bodily environment for pathogens, such as saliva and physiological conditions like body temperature; the innate immune response which deals with pathogens without requiring prior exposure to them; and the adaptive immune response which defends against unknown pathogens.

Recognition One of the key features of the immune system is its ability to identify and respond to a great number of different patterns. Recognition events involve molecular signals and protein structures. For instance, certain types of immune cells bear *receptor* molecules on their membrane surface which

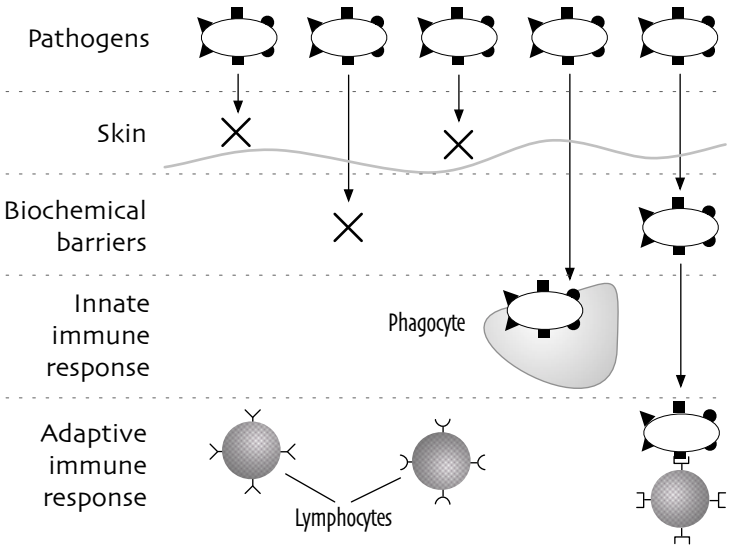


FIGURE 2.1: Multi-layered architecture of the immune system. Reproduced from [38].

bind to sites on the surface of pathogens, called *epitopes*. If the bond between receptors and epitopes is strong enough, then the immune cell is possibly encountering an enemy. To become fully activated, the immune cell must receive additional signals.

Feature Extraction Certain types of immune cells, called *antigen-presenting cells (APCs)*, are responsible for carrying out a process resembling feature extraction that allows recognition of infected host cells. APCs filter molecular noise from potentially harmful material, called *antigen*, so as to present other types of immune cells with important information regarding body cells.

Diversity Besides the variety at the level of different types of elements, such as cells, molecules and organs, and mechanisms that constitute the immune system, the set of receptors expressed by immune cells is also highly diverse. Approximately 10^8 different *lymphocytes*, cells that mediate adaptive immune responses, circulate within the human body. Each lymphocyte expresses about 10^5 receptors on its surface, all identical for a single lymphocyte but varying among the total population [67].

Despite this large number, though, the set of immune receptors is still incomplete when compared to the diversity of pathogenic epitopes that exist in nature. Thus, due to the limited manufacturing ability of the body, the immune system is unable to recognise unknown infectious microorganisms without some additional, special, process. This special process exists and assists with diversity in the immune system when an adaptive immune response is induced on first encounter with an antigen (primary response). *Somatic hypermutation* is a high-rate mutation process which immune cells undergo when proliferating in response to invading pathogens, and allows for the creation of new receptor patterns, extending the existing set of immune receptors.

Learning In the immune system, learning refers to its ability of becoming better at recognising new structures of specific antigen via a process called *affinity maturation*. This process involves increase in size of varying subpopulations of certain immune cell types (somatic hypermutation), followed by a selection pressure favouring those immune cells that have higher affinity, that is are more specific to the new antigen. This is why it takes several days for the immune system to develop a primary response to the first exposure to an unknown antigen.

Memory The high affinity patterns developed during a primary response remain in the body in the form of long living *memory cells* which circulate in a resting state for future use. In case the original specific or any structurally related antigen is encountered again, immunological memory helps to mount a very rapid and intense *secondary response*. Figure 2.2 illustrates the primary, secondary and cross-reactive immune responses in relation to *antibody*—the receptors of certain types of immune cells in a soluble form which bind antigens—concentration in the body and time. Cross-reaction describes the case where a more efficient secondary response is presented to an antigen that is similar in structure to a previously seen antigen.

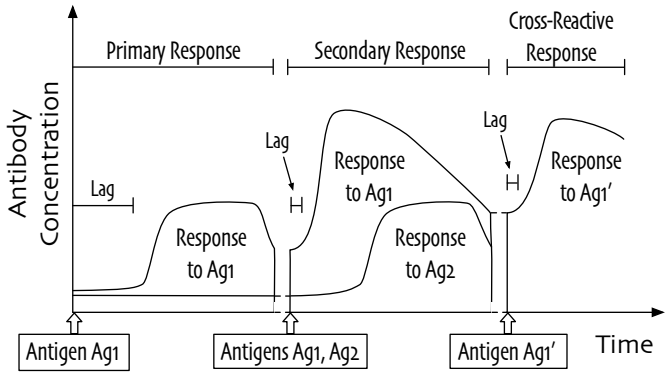


FIGURE 2.2: Primary, secondary and cross-reactive immune responses. After an antigen Ag_1 is seen once (primary response), subsequent encounters with the same antigen (secondary response) or a similar one $Ag_{1'}$ (cross-reaction) will promote a faster and more effective response not only to Ag_1 but also to $Ag_{1'}$. Reproduced from [38].

Distributed Function The immune system consists of a variety of elements: *lymphoid organs and tissues*, immune cells and molecules. These elements are distributed throughout the entire body. For example, the lymphoid organs, wherein lymphocytes develop and interact, are found in various places within the human body, see figure 2.3. Lymphocytes recirculate between the blood and these organs until they encounter their specific antigen. However, none of these elements is subject to any centralised control.

Autonomy Although the immune system is integrated into the body and coexists with other systems, such as the nervous and endocrine system, no external control or maintenance is applied on it. Rather, it functions autonomously and regulates itself using methods such as local cell interactions and cell population dynamics.

Disposability The continual renewal of immune cells and molecules shows that no individual component is essential for the functioning of the immune system. Single cells and molecules are expendable with the exception, perhaps, of memory cells which have long life spans.

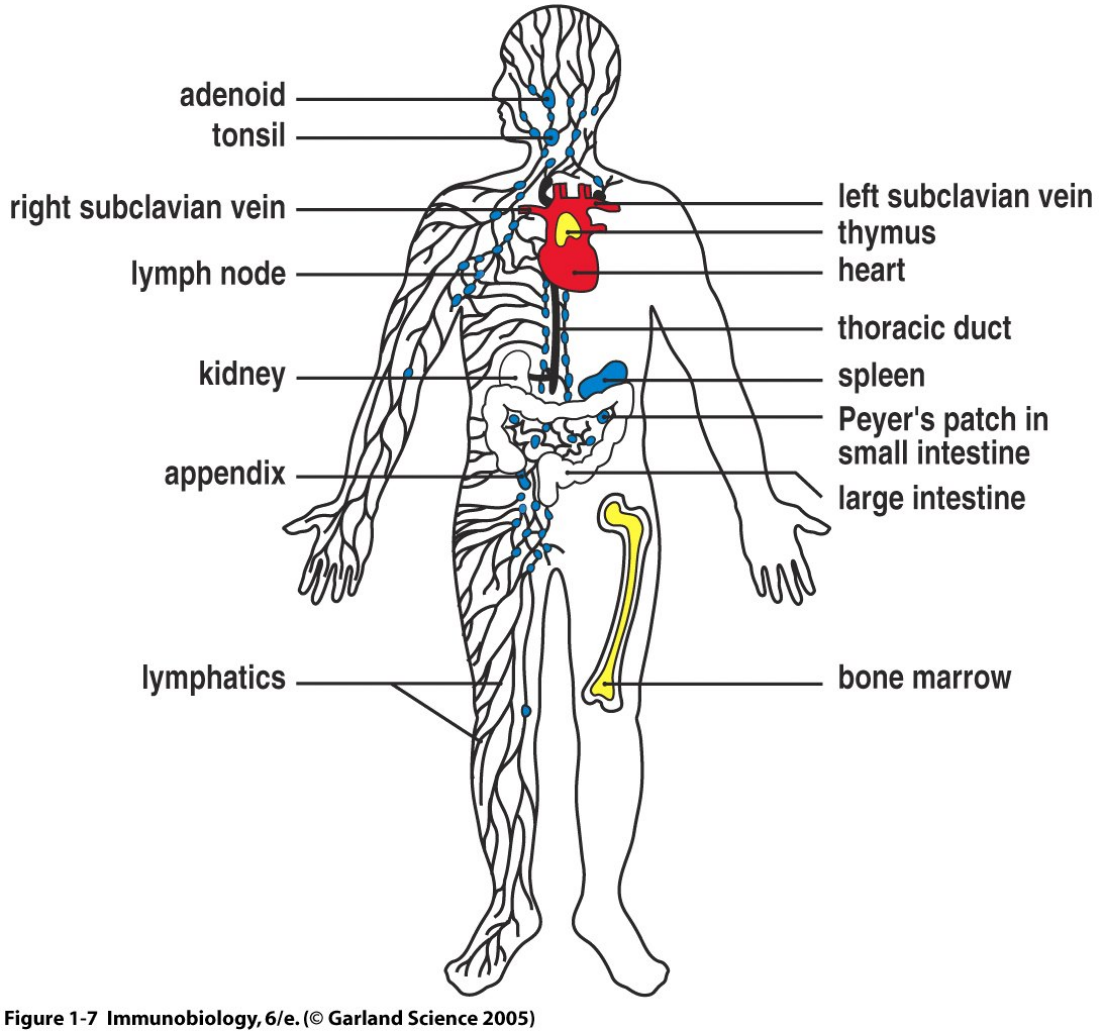


FIGURE 2.3: The distribution of lymphoid tissues in the body, reproduced from [72, p. 7].

Imperfect Detection The immune system is tolerant to molecular noise, since no absolute recognition of pathogens is necessary. Detection can be approximate, in that a receptor can bind with several different kinds of, structurally similar, antigens. This feature enables more flexible allocation of resources by the immune system, for example less specific lymphocytes can detect a variety of pathogens, but comes at the cost of being less efficient at recognising specific pathogens.

The immune system is considered by computer scientists a rich source of inspiration that embodies a powerful set of properties such as learning, adaptability and

self-organisation among others. The above immune properties indicate in what way the AIS literature considers the immune system to be interesting from a computational point of view. In addition to that, it is worth mentioning a perspective that comes from a completely different background, yet is equally interesting to consider. The discussion that follows briefly examines what Orosz [98] suggests the principles of network design that support immune function are.

2.2.2 Networked View

In [98] Orosz approaches the study of the immune system in a way that is rarely met among immunologists. He takes a step back from the prevalent purely biological view and poses questions considering the networked character of the immune system. He is interested in studying complex issues, such as how the immune system refrains from chaos, how it manages its own complexity.

Under this approach, he chooses to refer to *leukocytes*—the white blood cells upon which immunity depends—as a swarm, and highlights that immune responses are accomplished by mass action of these cells. Therefore, to appreciate how effective immunologic function arises from the immensely complex immunologic network, it is required to think about the subject in terms of beyond individual effort at the level of single leukocytes. In this context, Orosz presents what he calls *innate principles of network design and function* that provide immune networks with a variety of control options. These are summarised below.

Phylogenic layering is the accumulation of new immune processes on top of older ones that have proven less effective. Thus, the system is ensured with backup responses, reducing chances of complete failure. Two major design features arise from this principle. First, immune responses are organised in a *scaffolding* manner to progressively unfold and maintain their order. In general, early steps in the immune response create the specific conditions that permit or preclude the development of later steps in the response.

Secondly, an immune response is used only when, and if, the conditions that allow its use develop. This *conditional use principle* solves the difficult problem of providing specific immune components when required, at a particular location and time. In addition, it allows using the same component at different times for different purposes, a speculation that could explain the multifaceted role of elements such as *cytokines*—signals released by cells that can alter the behaviour or properties of the same or other cells.

In summary, phylogenic layering provides the immune system with a strategy for preparing itself to respond to virtually any pathogen without knowing its nature in advance, by stockpiling immune resources at the inflammatory site for later use. The fact that the immune system incorporates multiple response options indicates that no single prototypic mechanism exists that can mount an effective response to any given set of harmful antigens.

Parallel Processing is reflected on the immune system at two different scales. Firstly, many similar immune elements work on the same task simultaneously. This describes the concept of redundancy which supports the overall immune function in case of individual failures. Secondly, multiple mechanisms are used for the same task in parallel which allows the development of a broad-based, rapid response against pathogens of unknown number or identity.

Alternative strategies, such as attempting to identify the pathogen first, and then calling for pathogen-specific response elements, are deemed too risky for the immune system as valuable time may be wasted in incomplete or false pathogen identification. Instead, the immune system initially employs multiple responses concurrently and, as these mature, the most effective mechanism in the given situation is favoured. The other immune mechanisms fail to develop either due to lack of support or negative feedback signals.

The strategy of parallel processing comes at the price of using the immune resources in a wasteful manner. In addition, no guarantee can be made that the

resulting, most responsive, mechanism is also the best possible solution. Rather, the strategy results in developing the *best response possible under existing conditions.*

Dynamic Engagement relates to the transient role of leukocytes, when, during an immune response, large numbers gather at the inflammation site where they function briefly and then are replaced by similar ones. The departed leukocytes either emigrate from the site, enter an inactive state (anergy) or die (apoptosis). This phenomenon can be described as a primary leukocyte swarm function.

The brief operation and continuous renewal of dynamic engagement, again, may seem inefficient practice. However the supply of leukocytes is virtually unlimited but, most importantly, the immune system gains from this principle two benefits. Firstly, it is able to continuously monitor the inflammation site for the persistence of harmful antigens. Secondly, it is able to produce self-limiting local responses without requiring complex control mechanisms.

For example, in case of antigenic presence, leukocytes are alarmed and release stressful signals which cause more leukocytes to be attracted to the location of response in order to deal with the incident. By removing the initial activated leukocytes, the antigenic alarm is interrupted. If the problem has not been resolved, newcomer immune cells will also be alarmed, indicating the problem anew. Otherwise, in lack of 'fresh' stimulation, fewer leukocytes will gather and the response will gradually decline.

Variable Connectivity refers to the nonlinear connectivity among immune elements. It is related with physiologic homeostasis, that is, the tendency of the immune system to maintain a balanced state of the tissues in the face of perturbations. Evidently, the immune system does not operate in isolation; it is affected by physiologic damage and it, in turn, influences physiology via inflammation and immunity.

The way the immune system attempts to restore balance in the body whenever a perturbation occurs is by building a local immune network de novo at the site where a problem appears. Once its task is accomplished, this temporary immune network dissolves. This is where variable connectivity helps, by enabling the immune system to *adjust its function by varying the degree of connectivity among its elements*. The degree of connectivity is regulated by the controlled and conditional expression of molecular signals, some of which function as connectors, while others act as disconnectors. Thus, the immune system can adjust its responses, and its function in general, by fluctuating the strength of interconnectivity among its elements. From this point of view, homeostasis can be seen as a highly dynamic process.

The advantages of resiliency to unexpected changes and flexibility in the way the immune system attempts to correct these changes gained by this design principle are accompanied by several questions which are not yet understood. For instance, how does the immune system manage to build coherent responses without contradictory agendas, or how does it assure that the developing response pattern will turn out to be effective?

This was a short summary of the principles that underlie the networked character of the immune system, as proposed by Orosz [98]. In this approach, the immune system is described as "a complex, adaptive network, capable of cognition, conditional responses, and adaptation to change." Orosz also introduces two new immunologic areas that require investigation, as many of the workings of the immune system are still unknown and remain unexplored, especially in relation to its networked quality. The author presents *immuno-ecology* as the study of principles that allow the complex immunological network to exhibit effective immunological function. The principles discussed above belong to this area. *Immuno-informatics* is a complementary area which studies the immune system as a cognitive, decision-making system. In this area, the basic concept is

information in the context of the immune system, how it is extracted, processed, communicated and used to develop functional *immuno-ecology*.

2.3 Theories

2.3.1 On Immunology

In [21, p. 11–79], Carneiro presents an overview of the foundations of the field of immunology and indicates that current immunological thinking is essentially driven by two incommensurable conceptions of immunity. The first originates in the clonal selection theory, proposed by Burnet around the 1950s, and is grounded on the 'self' metaphor, that is, it assumes the existence of a clear-cut bounded immune self which fights against anything foreign. The second conception is built upon the idiotypic network hypothesis, proposed by Jerne in the 1970s, which claims that immunity is a result of perturbations that affect the internal organisation of the immune network. Thus, at one end of the spectrum it is thought that the discrimination between self and non-self is a necessary condition for immune function; a dormant immune system is only triggered to respond when it recognises a foreign entity, after the elimination of which immune activity ceases. At the other end, the distinction between self and non-self is discarded altogether, and it is thought that the immune system is an integrated network that senses itself and reacts when the balance of its intricately inter-connected components is disturbed.

Similarly, according to Tauber [124] immunologists today appear to be falling along various points of the continuum described by the positions of Jerne and Burnet. For instance, from his experience of studying autoimmunity, observing active immune cells during normal settings, Cohen concludes that the immune system is doing a lot more than just attacking foreign pathogens. As a result,

Cohen argues, the self-non-self discrimination is not obligatory for immune function. Rather protection against pathogens is only one of the many immune tasks that, ultimately, contribute to the *maintenance* of the body. Matzinger, another immunologist, although not as close to Jerne's conception as Cohen, opposes, according to Tauber, Burnet's supporters as she associates the trigger of immune reactivity with danger rather than with the explicit recognition of non-self, insisting that *context* plays a crucial role in immune function; if the context is generic danger and destruction, then an immune reaction is on the way.

A characteristic example of the disputes that exist within immunology is given by Matzinger [88], who deliberately avoids to explicitly define 'self' within her danger model because it is a controversial concept for immunologists to such a great extent that at an immunological workshop participant immunologists could not agree to a commonly accepted definition of self, even for the duration of the event. Another interesting example that illustrates the debate between immunologists today is presented by Andrews [7, p.83–85], captured from the recent immunological research literature. It appears that the disagreements extend beyond the semantic level that Matzinger [88] discusses. There seem to be fundamental differences at the level of methodology, that is, in the way immunologists consider research should be conducted. Andrews presents in [7, p.85] direct quotes from Cohn and Cohen which show the former's objection to the use of modelling as a means of understanding biological complexity, and the latter's embrace of mathematical modelling and computer simulation as helpful methods for understanding the immune system.

2.3.2 Immunology within AISs

The perplexities with which immunology is faced has not held computer scientists back from pursuing the development of a new computational intelligence paradigm based on the natural immune system. The two main conceptions of

immunity that drive present immunological thinking, described in the previous section, have, as one would expect, moulded the initial growth of the field of AISs.

From [38], it is clear that the majority of AIS algorithms have been derived either from the notion of self-non-self discrimination forming a family of population-based solutions, or from the idiotypic network concept leading to another group of network-based solutions. Similar trends are also identified in the literature review of immune-inspired approaches to ad hoc wireless networks, discussed later on in section 2.4.2.2. With respect to the biological mechanisms of the immune system, the focus of both of these influential conceptions is largely on, what is called in immunology, the *adaptive* arm of the immune system, namely on the immune cells and processes that are involved in specific responses against particular pathogens [72, chap. 1].

There have been suggestions recently within the field of AISs advocating a reexamination of the nature of the sources of inspiration on which AISs have been focussing the past years. For instance, Bersini reiterates in [15] his position with respect to the 'self' metaphor, which has gained great popularity within AISs. The author considers that such interpretation of the immune system is not the most fruitful one and encourages the AIS community to pay more attention to the self-assertion view for it has more potential to achieve success in an engineering perspective—the self-assertion view is largely a continuation of Jerne's idiotypic network and dismisses any notion of prior arbitrary division applied to the immune function, such as the self-non-self dichotomy.

Another invitation to the AIS community is expressed by Andrews and Timmis [8], who urge the AIS researcher to reconsider the starting point of AIS design with regard to immunological inspiration. From their investigations into the contemporary immunological research literature and projected to the current common AIS practice, the authors suggest that alternative immune theories should be examined; theories that are beyond immune ideas such as the self-non-self discrimination, which have dominated AISs and which appear to be debatable

within immunology itself. As an example, the authors summarise Cohen's view of immunity and highlight a number of ideas which, they consider, offer to the field of AIS opportunities for exploiting the immune metaphor in new ways.

Twycross and Aickelin present in [131] their own view on the subject of sources of inspiration for future AISs. The authors agree with the observations made by Timmis [126] with regard to the dead-end state of the AIS area,[1] and argue that one way to produce more effective AISs is to draw inspiration from the immune systems of relatively simpler organisms, such as plants and invertebrates, instead of focussing on the extremely complex workings of the human immune system. In addition, they suggest that AIS researchers who focus on the human immune system should employ more contemporary and sophisticated models, as these consider not only the adaptive but also the *innate* arm of the human immune system. The authors also present an outline of such immunological views, including Matzinger's danger model and Cohen's cognitive paradigm.

Finally, Neal and Trapnell [97] lay stress on the complex character of the immune system, which has been largely ignored by AIS researchers. To illustrate their point, they attempt to characterise some of the major actors and interaction mechanisms that have been identified by immunologists, of which only a few seem to have captured the attention of computer scientists so far. The authors consider that the properties of the interactions that occur within the immune network, as explained by Cohen, are worth being placed at the centre of the exploration by the AIS researcher, if development of AISs is to be furthered.

[1] These are discussed in detail in section 2.5.1.

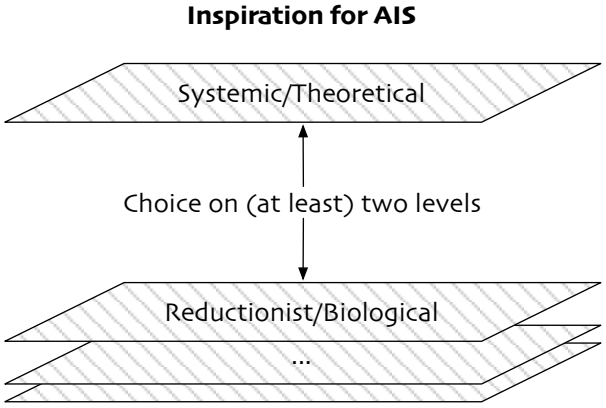


FIGURE 2.4: Example dialectical scheme for communication within the AIS community. Immunological inspiration involves decisions, intentional or otherwise, made on at least one of two levels related to: the biological details of interest, and/or the theoretical context. Such scheme can be augmented with additional dimensions, such as the application area or system of interest.

2.3.3 Discussion on Inspiration

Dialectical Scheme

High-level properties of the immune system, such as the ones reviewed in sections 2.2.1 and 2.2.2, may attract computer scientists or engineers to closer examine this particular biological system for inspiration. The gap between the interested researchers and the immune system can be partly filled with the existing body of AIS literature. More keen researchers may start digging directly into the immunological literature. In any case, given the situation in immunology and the suggestions from AISs, outlined in the preceding sections, the interested researchers are faced with good chances of becoming disoriented, confused and lost during their efforts to focus on some aspect of the immune system.

To the best of the author's knowledge, there has been no interest or need identified by the AIS community to promote a commonly accepted scheme for facilitating discussions on the available sources of inspiration from immunology. The author proposes that such a scheme should incorporate at least two levels, a *reductionist/biological* and a *systemic/theoretical*, see figure 2.4. Given the fact that the

majority of AISs involve decisions, intentional or otherwise, made on these two fundamental levels, the author suggests that it would become easier to reason about the nature of the various sources of inspiration and assess suggestions on the issue. Ultimately, such a dialectical approach can help the interested researcher to make more informed choices along the way of seeking inspiration from the immune system.

The discussion continues using the scheme of figure 2.4; any choice or suggestion regarding immunological inspiration for AISs involves decisions on at least one of two levels relating to biological detail and/or theoretical context.

Critique

When the intention of drawing biological inspiration is primarily associated with some theoretical context, then the scope for decisions at the biological level may become limited and biased, as some theoretical paradigms concentrate more on specific low-level mechanisms or processes over other. Such an example is the self-non-self discrimination concept, the focus of which historically revolved around the adaptive arm of the immune system, as it was thought that the adaptive immune cells were the initiators of an immune response. Matzinger [88] presents an interesting historical review that highlights the influence of the 'self' metaphor on the direction of immunological research over the years. The workings of the adaptive immune response were being studied intensively by immunologists, whereas anything related to the innate arm was ignored. Inevitably, inspiration choices based on the 'self' metaphor that were made by AISs researchers in the past focussed on biological mechanisms that involved almost exclusively adaptive immune elements and processes.

Recent advances within immunology have shifted the centre of attention to the innate immune system. Matzinger's [89] danger model has promoted a certain type of innate immune cell to the position of initiating an adaptive immune response,

contradicting thus the constitutive activation element which the adaptive immune cells are thought to have within the self-non-self discrimination paradigm. The suggestion by Twycross and Aickelin [131] to the AIS community, to pay more attention to the human innate immune system, can be attributed to the influence of the danger model on the authors, although no explicit link is stated in the publication between the biological part and the theoretical context.[2]

While there is no reason why it should be expected that any biologically oriented suggestion, and indeed research in general, for inspiration within AISs be associated with a specific theoretical view, if certain assertions are being made to justify the suggestion, then the clarification of one's positions on both levels should be considered necessary. Twycross and Aickelin [131] support their proposal for inspiration from innate immune mechanisms based on the claim that these "control the adaptive immune system in biological organisms." Although such a claim may make sense for the human immune system when viewed within the danger model, it is, for example, completely arbitrary within the context of Cohen's cognitive view, as explained later on in section 4.4.1.

An interesting contrast to the suggestion by Twycross and Aickelin [131] is the call by Neal and Trapnell [97] who draw attention to the interactions that occur within the immune system. In this case, it is clear that the discussion's general theoretical context stands mainly on Cohen's ideas of immunity. Besides the differences with respect to what the authors consider the immunological point of focus for future AISs should be, the two publications differ with regard to another fundamental, and admittedly difficult, subject, that of *demarcation* of immune function. Whereas Twycross and Aickelin [131] freely unfold their suggestion based on distinctions such as the 'innate' and 'adaptive' immune system, Neal and Trapnell [97] are hesitant to express their ideas by identifying definite 'subsystems.'

[2]The involvement of the authors in the 'Danger Project' [2, 130], an interdisciplinary project investigating the link between AISs and intrusion detection systems, inspired by Matzinger's danger model, makes this assumption safe.

2.4 Artificial Immune Systems

2.4.1 Introduction

To the best of the author's knowledge, the fields of AISs and Speckled Computing have not been examined *in parallel* before. The same seems to be the case for AISs and WSNs. There has been research, albeit limited, *across* the two fields. However, within the AIS community in particular, the area of WSNs remains largely unexplored. Due to the limited examples of immune-inspired work on WSNs, the studying criteria are broadened to include work that involves (mobile) ad hoc networks, of which a WSN is a subclass.

The literal meaning of an ad hoc network refers to the quick setup of a communication network for a specific purpose. Mobile ad hoc networks (MANETs) are typically regarded as having wireless multi-hop communication and nodes that are mobile, and are usually formed on demand in cases such as disaster relief operations or large construction sites. The distinction between MANETs and WSNs lies on differences that include the presence of users in the former or the stricter energy considerations of the latter. For a more detailed discussion on the two networking concepts see [76, p. 10–12].

This section examines existing work that adopts an immune-inspired approach in order to deal with issues related to WSNs and (mobile) ad hoc networks. Before continuing, it is important to clarify the angle from which the relevant literature is examined. This review is not targeted at evaluating the performance of the proposed immune-inspired solutions per se. As is typical of AISs [61, 127], the set of types of problems explored is rather diverse even in this small collection of research attempts that were found on the subject. Therefore, it is hard to present an in depth critique of the solutions for each of the individual problem domains discussed. Besides, such an analysis is beyond the scope of this thesis.

Instead, the intention is to analyse the way the literature has perceived and treated the potential of bringing together the immune system and ad hoc wireless networks as well as the association trends that have emerged so far between the two systems. In this regard, the structure of the review is based upon two dimensions. The first one is the type of problem attempted to be tackled. The other dimension relates to the immunological theory or principle from which inspiration is drawn.

Unlike other biologically inspired computational techniques, such as genetic or ant colony algorithms, an artificial immune system does not adhere to a core set of abstracted rules that principally model the underlying natural system. The reasons for this are to be traced back to immunology, the field of study of the human immune system and, of course, to the immune system itself.

As already discussed in section 2.3, several theories have been postulated by immunologists over the years, forming various schools of thought on how the immune identity and function should be defined. Some of the proposed immune models have dominated the field of immunology for longer, influencing the direction of immunologic research. This, in turn, has naturally shaped the field of AISs, the majority of which has primarily focussed on the popular principles offered by clonal selection theory [20] and immune network theory [73]. These appear to be the dominant sources of inspiration in the set of works involving WSNs and (mobile) ad hoc networks that were studied.

Yet another reason behind this lack of a typical AIS algorithm that uniquely characterises the field is, in essence, the immune system itself. It involves an array of mechanisms that function in intricate and not fully understood ways, causing great confusion within immunology but offering, at the same time, a rich source of inspiration for computer scientists and engineers.

2.4.2 Taxonomy

2.4.2.1 Based on Type of Problem

The pervading conception of the immune system to the public is that of a fighter, and justifiably so, since whenever people become ill they expect their immune system to free them from the virus they have contracted, or they agree to be vaccinated in order to ensure their immune system will be well prepared to successfully fight away future infections. As such, the idea of a protective part that ensures the security of an autonomic system, such as an ad hoc wireless network, is directly linked with the provision of an artificial immune system which will undertake the role of the protector from within the autonomic system.

This proposal has been made independently by [18, 43]. In [18] the authors propose a self-healing system architecture for a hybrid sensor network—a network consisting of sensing and monitoring nodes, base stations and database machines—inspired by the adaptive immune system. This architecture sits above the network layer and provides a whole-network approach to robustness, by encompassing automatic fault recognition and response over a wide range of possible faults. The authors of [43] present a four-layer architecture for ad hoc wireless networks, the purpose of which is to establish a high degree of survivability by aiming at universality, that is, the architecture is not restricted to particular protocols.

Whereas the proposal by Bokareva et al. [18] appears not to have been taken beyond the initial proposal, subsequent work by Drozda et al. [43] focus on exploring the issue of detecting node misbehaviour in a WSN by employing mechanisms based on AISs [42, 44, 45, 118]. The first attempt at investigating the use of an AIS to detect node misbehaviour in the general area of mobile ad hoc networks seems to be by Le Boudec and Sarafijanović [84], who consider the problem of detecting nodes which do not execute properly the routing protocol (Dynamic Source Routing protocol (DSR)) employed by the network. Similar

security challenges have been examined by others too. For example, Kim et al. [78] investigate the vulnerabilities of the flooding behaviour of another, popular in WSNs, routing protocol (Directed Diffusion). Mazhar and Farooq [90] develop an AIS-based security system for countering attacks in the context of a nature inspired MANET routing protocol (BeeAdHoc).

On a different note, Atakan and Akan [11] examine the problem of adaptive sensor data gathering in WSNs and propose an immune-inspired method for distributed node and rate selection (DNRS). Lau and Lai [81] propose an immune-based control algorithm to enable sensor nodes in a WSN to track objects in an energy efficient manner. The possibility of tracking mobile search and rescue robots by an AIS-based distributed WSN is examined by Ko et al. [80], who utilise an immune-inspired framework developed for controlling decentralised systems. Finally, Chen [23] presents an AIS-based network middleware for autonomous structural health monitoring by sensor networks, which incorporates an artificial immune pattern recognition methodology for structure damage detection and classification.

From the above listing it is clear that the most popular application area where ad hoc wireless networks and AISs cross is that of anomaly detection. The most influential works coming from the AIS field appear to be the development of an AIS for computer security in wired local area networks by Hofmeyr and Forrest [68, 69], along with the proposal by Aickelin et al. [2] for an AIS-based intrusion detection system, founded on the 'danger' immune hypothesis. However, there are a number of instances in which the motivation for adopting an immune-inspired approach is attributed to interesting immunological properties, such as autonomy, learning and dynamic character.

Table 2.1 summarises the types of problems associated with ad hoc wireless networks for which immune based solutions have been explored, discussed in the review.

Application Area	Type of Problem
Security:	Misbehaviour detection [42, 44, 45, 84, 118] Routing attacks [78, 90]
Control:	Data gathering [11] Object tracking [80, 81]
Other:	Structural health monitoring [23, 24]

TABLE 2.1: Problem domains where ad hoc wireless networks and AIS meet in existing literature.

2.4.2.2 Based on Type of Immunological Theory

From studying the literature, it is evident that the majority of immune-based approaches to ad hoc wireless networks do not employ a direct study of the theoretical, experimental nor even the so-called 'textbook' immunological literature about the workings of the immune system. Instead, in most cases the work is built upon existing interpretations and abstractions as derived by AIS practitioners. Given the apparent sources of influence originating in the AIS field, identified in the previous paragraph, the type of immunology that has filtered through to immune-based work in ad hoc wireless networks is primarily focussed on the immunological ideas of the self-non-self discrimination, followed by the danger-signals hypothesis and the immune network theory.

Initial work in the application area of security [44, 45, 84, 90, 118] has been largely shaped by the negative selection algorithm developed by Hofmeyr and Forrest [68], which uses immune-cell based detectors to distinguish between normal system behaviour (self) and potentially abnormal incidents (non-self) in networked computers. Subsequent attempts [91, 114] to improve on previous work concentrate on incorporating the notion of danger signals which, according to the position paper by Aickelin et al. [2], can help provide intrusion detection systems with balance and correlation between key types of alerts. Others [78] have directly applied the dendritic cell algorithm, a danger-theory based AIS developed by Greensmith et al. [55] for anomaly detection, to sensor networks with the aim of detecting routing attacks.

Immunological Theory	Employed AIS
Self-non-self discrimination:	Negative selection algorithm [23, 44, 45, 84, 90, 118], CLONALG and AIRS [23, 24]
Danger-signals hypothesis:	- [91, 114], Dendritic cell algorithm [78]
Immune network theory:	Idiotypic network model [11, 81]
Other:	General suppression control framework [80]

TABLE 2.2: Taxonomy of immune-inspired works on ad hoc wireless networks, organised in terms of immunological theories and employed AISs.

Outside security, though still within the domain of anomaly detection, [23, 24] adopt for their sensor network a classic self-non-self organisation based on the clonal selection principle and develop a structure damage classifier based on two AISs: a pattern recognition algorithm (CLONALG) by de Castro and Von Zuben [39], and an immune-inspired supervised learning algorithm (AIRS) by Watkins et al. [136].

Works in the application area of control have utilised the modelling equation of immune (idiotypic) networks derived by Farmer et al. [49], who investigate the factors that contribute to the stimulation level of a specific immune cell type. The dynamics of activation and suppression described by the model of Farmer et al. have been applied to the selective node designation for sensor data transmission and the further regulation of their reporting frequency in [11], as well as to the decentralised object tracking by sensor nodes which switch between active and inactive mode based on predefined stimulation factors in [81].

Lastly, a noteworthy exception is the work by Ko et al.. In [79, 82], the authors develop a General Suppression Control Framework (GSCF) for decentralised mechanical control, such as controlling modular robots, based on the concept of immune cell suppression. This framework is subsequently applied to a distributed WSN for robot tracking in [80].

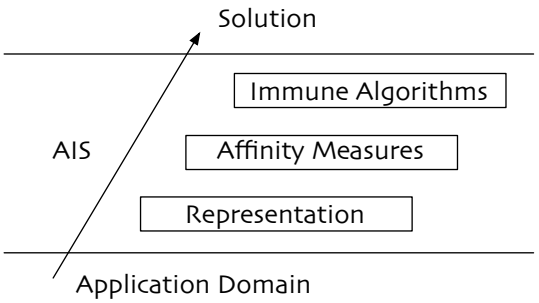


FIGURE 2.5: Layered framework for AISs. Reproduced from [38].

Further details on the various immunological theories and immune algorithms mentioned above can be found in the overview article of artificial immune systems compiled by Timmis et al. [128]. Table 2.2 summarises immune-inspired works for ad hoc wireless networks, based on the type of immunological influence in terms of theory and employed AIS.

2.4.2.3 Critique

Despite the fact that most of the reviewed works use off-the-shelf immune-based abstractions and models, they indicate a growing interest in the direction of exploring immune-inspired solutions for ad hoc wireless networks, an application area that has drawn little attention among AIS practitioners. The original AISs employed in these works were developed to solve problems similar in principle but different in terms of application settings. Because of this, they require some form of adaption in order to be applied to the engineered networked system.

In particular, with respect to the layered framework for engineering AIS proposed by [38, p. 60–61], shown in figure 2.5, the representation layer, that is the mapping of and representation for the components of the system, is being defined independently virtually in every work. In addition, the layer of immune algorithms undergoes the necessary variations so as to be adapted to the individual cases, or extended to improve on or overcome issues with the initial AIS-based implementation.

An example of modifying the original AIS for adapting it to the WSN environment is the work by Kim et al. [78], who suggest the use of the dendritic cell algorithm [55] for detecting routing attacks. The authors are motivated by the application of the original AIS to the problem of port scanning in [56], in which the monitored system elements are process IDs (antigen) and a collection of input signals that describe the machine behaviour (context).

Kim et al. map the notion of 'antigen' to the routing packets and use as 'context signals' quantitative measures that are chosen to reflect the routing behaviour of the network, tailored to the specific attack under study. The product of their work is a variation of the original immune algorithm, and is called the ubiquitous dendritic cell algorithm [78] which, according to the authors, appears to be an attractive solution for detecting malicious activities in sensor networks.

In some cases, though, there is a mismatch between the qualities of the employed AIS algorithm and the requirements of the application system, or immunological concepts are misunderstood leading to development of solutions that are hard to reason about in relation to the underlying immunology. For example, in [115] Sarafijanovic and Le Boudec utilise the principle of negative selection in the context of the self-non-self discrimination model to tackle node misbehaviour detection in MANETs. Given the dynamic nature of MANETs, where topologies may change fast, and their typical use in emergency situations, where communication is established on demand, a network security solution that requires prior to deployment training in a safe environment is impractical.

Another example illustrating a solution that is complicated and confusing due to misconceptions is the work by Mazhar and Farooq [90, 91], who investigate the development of an AIS-based security framework to detect and respond to routing attacks in MANETs. In [91], the authors present an improved version of their initial self-non-self solution [90], based on the behaviour of dendritic cells as proposed by the 'danger' theory. They, essentially, claim to model the functionality of tissue-sampling dendritic cells to tolerise or activate T cells during

their maturation process in the thymus. Section 5.4 explains why dendritic cells are not thought to activate T cells within the thymus, and why dendritic cells that reside in the peripheral tissue are known for presenting their findings to T cells in lymph nodes rather than in the thymus.

2.4.3 Summary

The literature reveals there has been limited research involving immune-inspired approaches to WSNs. There has been an attempt to introduce sensor networks as a promising application area for AISs by Kim et al. [78], but it has had little impact within the AIS community. The majority of the approaches reviewed adopt existing immune-based abstractions either developed from (negative selection principle) or popularised by (idiotypic network model) AISs. In other words, there is very little original investigation done directly into immunology.

Moreover, the literature shows how well-established the fighting aspect of the immune system is. Although it is unwise to discount research emanating from the defensive character of the immune system, it is nevertheless limiting to regard this as the only analogy to derive from immune function when seeking biological inspiration for solving computational or engineering problems. Notable exceptions that offer contributions to refreshingly diverse problems in WSNs are inspired, for example, by the regulatory aspect of the immune system [11, 81].

Attempting to transfer existing solutions that were initially designed for completely different systems to the demanding environment of (mobile) ad hoc networks has its pitfalls, such as focussing on immunological interpretations that are unsuitable for the problem under study, or developing complicated designs based on misconceptions about immunological functionality. The following section discusses the current thinking within AIS with regard to principled ways of exploiting the immune system, that is, how to practice AIS development.

2.5 On Methodology for AISs

Artificial immune systems are in a unique position within biologically inspired computing in that they focus on a complex biological system that still is a long way from being fully described by immunology and the function of which emerges from a wide selection of biological elements involved in an equally wide range of elusive processes. These facts in conjunction with the unstructured way of conducting research over the first decade of the AIS development, recently led part of the community to advocate that the AIS field requires a shift in the way it performs its practice if further progress and growth of the field is to be enabled.

2.5.1 Approaches

The layered framework of figure 2.5, proposed by de Castro and Timmis [38], is perhaps the first attempt to create a common basis for AISs. At the time of its proposal, the design focus of many AISs was problem-oriented, something which is reflected in the framework as its starting point for building an artificial immune system is rooted in the application domain of interest. The elements included summarise the state of the art of AIS research around that time, which primarily concentrated on the development of population and immune-network based algorithms for learning, memory and anomaly detection.

A later proposal by Stepney et al. [122, 123] suggests a more generic conceptual framework for developing bio-inspired algorithms, illustrated in figure 2.6. The drive behind this proposal stems from the realisation that the direction of early AISs, such as [17, 51] which were fruit of interdisciplinary work between immunologists and computer scientists, was largely abandoned in subsequent AISs in favour of the so-called 'reasoning by metaphor' route. This less sophisticated approach proceeds to developing bio-inspired algorithms directly from biological inspiration.

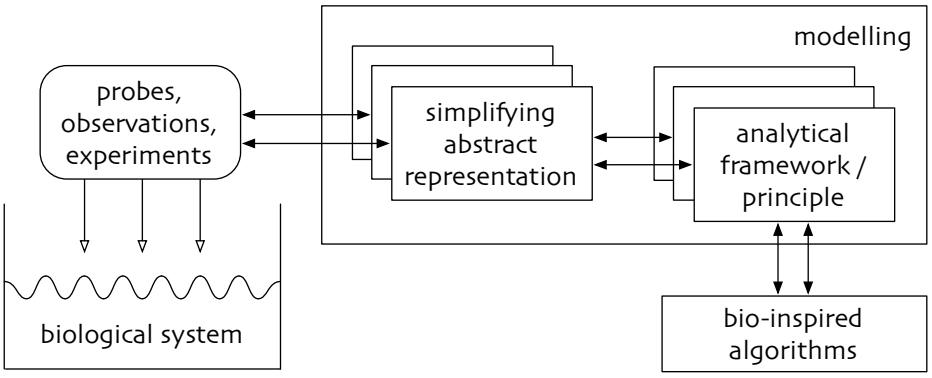


FIGURE 2.6: An outline conceptual framework for a bio-inspired computational domain. Reproduced from [123].

Stepney et al. argue that in order to increase the chances of capturing those properties of the biological system that contribute to the desirable observed behaviours, AIS practitioners need to return to an interdisciplinary mode of research. By having closer interaction with other domain experts, such as biologists and mathematicians, the authors argue that more sophisticated biological models and analytical computational frameworks can be generated to provide principles for designing and analysing bio-inspired algorithms. Furthermore, it is argued that the modelling component of the conceptual framework can also be beneficial to biology, as it can help advance the understanding of the biological system under study and possibly yield questions biologists have not considered before.

In [126], Timmis reflects on the area of AISs and argues that the field has reached an impasse. The author raises a number of issues, such as the limited view of the immune system that prevails the field and the lack of theoretical work and thought regarding the application of AISs, and proposes future challenges to the AIS community. In particular, the challenges discussed refer to the methodology employed in the development of AISs, concurring with the position of Stepney et al. [123] on reinforcing again collaboration between AIS practitioners and immunologists with the aim of developing novel and accurate metaphors, but also being a benefit to immunology.

In addition, the author encourages development of theoretical basis for AISs in

order to help understand their nature and where they are best applied. Furthermore, attention is drawn to the fact that the immune system interacts with other systems, such as the neural and the endocrine systems, which, if considered, can help open new avenues for AIS research. Finally, the author urges to show consideration when choosing an application area, to aim for types of application where the benefit of adopting the immune approach is clear.

According to the author, several people from the AIS community have contributed to the expression of many of the ideas presented in [126], and, indeed, some of the challenges described above seem to have formed the basis upon which the vision of *immuno-engineering* [129] stands.

The immuno-engineering approach is a recent proposal by Timmis et al. [129], suggested as a new way of thinking about the development of immune-inspired systems. Following the concepts of 'immuno-ecology' and 'immuno-informatics' by Orosz [98], presented in section 2.2.2, the authors define a new kind of engineering that exploits principles derived from the immune system to enable the engineering of artefacts with properties analogous to those provided to organisms by their natural immune systems.

Key objectives of immuno-engineering include the creation of immunological models, both mathematical and computational, which capture the interplay among the various immune components from the individual to the populations and systems level. These models, it is argued, will then lead to the development of a library which acts as a bridge between experimental immunology and engineering, see figure 2.7. The immuno-engineering library will serve the dual purpose of, firstly, aiding the development of more biologically faithful AIS solutions and, secondly, of helping inform experiments within the biological domain, improving thus the understanding of the immune system. Lastly, the authors advocate that the library should be deployed and evaluated in a diverse set of case studies within application areas that exhibit the future AIS features, discussed in chapter 1.

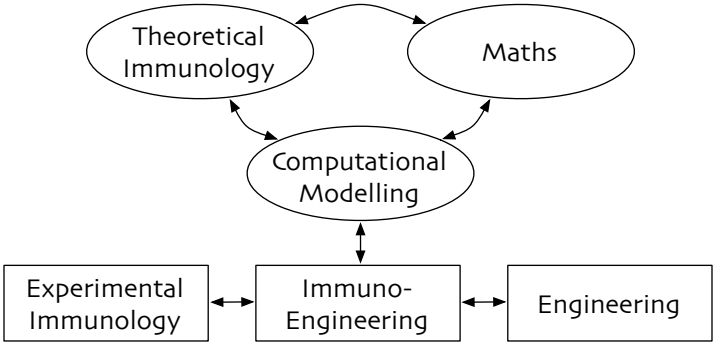


FIGURE 2.7: Interactions between disciplines that lead to the development of immuno-engineering which itself acts as the bridge between experimental immunology and engineering. Reproduced from [129].

Timmis et al. [129] underline the importance of adopting the conceptual framework for AISs in order to formulate the abstraction process of future bio-inspired algorithms in a principled way. In this respect, the immuno-engineering approach is in line with Stepney et al. [123], in that both proposals strongly advocate the need for cross-domain interactions between computation, mathematical analysis and biological experimentation. Timmis et al. [129], though, stress the consideration of an additional dimension, that of adopting a problem-oriented perspective alongside the development of AISs [53], as design of generic AIS algorithms can be a difficult task without having a particular end application in mind to provide direction to the modelling work. Thus, where the conceptual framework approach considers the starting point towards a bio-inspired algorithm to be probes into biology, immuno-engineering advocates choosing and examining the application area first [83]. Nevertheless, both approaches share a common ultimate objective, that of generating AISs that truly embody the computationally interesting qualities of the immune system.

2.5.2 Examples

Since its proposal, the impact of the conceptual framework on the AIS community has started to show in several publications which attribute their methodological approach to the framework. However, there yet seems to appear a research work

within the field of AISs that follows and practices the ideas and suggestions of the conceptual framework to the full extent. Next are presented selective examples from the AIS literature which illustrate the influence that the conceptual framework has had so far.

Perhaps the most complete utilisation of the conceptual framework approach, in terms of methodological guidance, to this date is the work by Andrews [7], who explores the development of an AIS based on novel immunology by explicitly following the key ideas of the conceptual framework. The author, essentially, presents an example of full instantiation of the conceptual framework employed in the context of a case study, investigating at the same time the systematic aspects of the framework itself.

Andrews [7] first passes through the stages of probing and modelling in order to identify and further investigate novel immunological concepts. This process is repeated in search of a more useful computationally model, after the determination of which the author proceeds to the last two stages of the conceptual framework. An analytical computational framework is created based on the model of the previous stage, which is instantiated to produce a pattern classification algorithm. Unfortunately, this work lacks interdisciplinary perspective, a requirement that is central to the specifications of the conceptual framework. The author acknowledges that the issue of domain expertise is of key importance, but states that such an approach was not possible for the work presented in [7].

Other works embrace the call of the conceptual framework for a more principled way of research by performing a theoretical or empirical investigation. Owens et al. in their lineage of work [99, 100, 101] apply modelling techniques to an immunological hypothesis, related to the activation of T cells. After having developed and validated models of T-cell receptor signalling, they show how these can be used to derive a kernel density estimation method for anomaly detection. Another example is the work by Read et al. [111], in which they present a preliminary empirical investigation of the parameters of an artificial cytokine network,

a mathematical model of the interaction of cytokines and immune cells derived by [70]. The aim of their work is to assess the suitability of the system for deployment in an engineering context. The authors found the system to be unsuitable for use in engineering in its current form, due to its sensitivity to parameter adjustments causing unpredictable behaviour. Finally, it is worth mentioning the work by Greensmith [54], although no explicit reference of influence is made to Stepney et al. [122], as it is one of the few recent research efforts that developed an AIS algorithm from close collaboration with experimental immunologists.

Being a more recent proposal, the immuno-engineering approach [129] has not had the chance yet of shaping research practice within AISs. An exception to this is the work by Lau et al. [83] who introduce their interest in investigating anomaly detection in swarm robots within the context of immuno-engineering, by undertaking the initial stage of examining and understanding the problem domain before looking at immunology for inspiration.

2.5.3 Modelling within AISs

Computational modelling of the immune system may be performed specifically for the purpose of biological simulation, or it may be used by computer scientists in their exploration for immune-inspired solutions. Different research goals and reasons behind developing an immunological model define different levels of abstraction and fidelity of the referenced biological observations.

Within the area of AISs, several publications have drawn attention to the importance of modelling the immune system besides Stepney et al. [122]. For instance, Bersini [16] motivates the AIS community to make a shift from problem-solving (engineering solutions) to the perspective of modelling immunological aspects for the study of emergent phenomena or simply for pedagogical purposes. In any case, such a shift, is argued, will help strengthen again the partnership with immunologists from where the original AISs arose. Timmis [126] highlights the

importance of modelling in enabling the field of AISs to both make contributions to immunology and fully exploit the immune metaphor.

A number of modelling tools have been used to construct computational immunological models, varying from object-oriented techniques to more formal approaches. For example, Read et al. [112] utilise UML [52], an object-oriented diagrammatic language coming from software engineering, to produce an initial model of an autoimmune disease and its regulatory network. Owens et al. [100] for their modelling work on T-cell signalling use the stochastic π-calculus [106], a process algebra used to specify concurrent computational systems with the property of mobility. In [50], Forrest and Beauchemin review some of the computational approaches that have been applied to immunological modelling. They focus on agent-based modelling and discuss cases where ideas from these models have been employed in order to solve practical engineering problems. Further examples can be found in other reviewing works, such as [128] and [7, p. 69–74].

Whereas modelling techniques of mathematical nature, such as the π-calculus language, are especially suited for describing biology at the level of populations, bottom-up approaches, such as agent-based modelling, are better for representing individuals. For instance, a model in π-calculus is composed of processes which describe types of molecules or cells, and shared channels which represent reactions between the different types of processes [100]. Such an environment lends naturally itself to the investigation of population behaviours, their dynamics and interaction properties. On the other hand, an agent-based model consists of entities which explicitly represent individual molecules or cells, the behaviour of which is encoded as a set of rules [50]. An environment like this provides a spatial element which allows the study of agent behaviours that arise from local mechanisms and interactions.

The notion of individual agents governed by predefined rules in a spatial virtual world is intuitively closer to the concept of specks operating under instructions

delivered by preloaded firmware, situated within a physical environment. For that reason, in this thesis the agent-based approach to modelling is adopted.

2.6 Conclusion

This chapter has:

- introduced the immune system as viewed in computational terms by the AIS field and in networking terms by Orosz,
- reviewed the dominant immunological theories and discussed their impact on AISs,
- reviewed existing literature on the joint subjects of AISs and WSNs,
- discussed methodological approaches to developing AISs and identified agent-based modelling to be a suitable technique for use as part of the investigation in this thesis.

The next chapter examines WSNs in detail with a focus on specknets.

Chapter 3

Wireless Sensor Networks and Specknets

3.1 Introduction

This chapter introduces the domain of WSNs with a focus on specknets. Section 3.2 defines WSNs and their role. Section 3.3 introduces specknets and discusses their relation to WSNs. Section 3.4 deals with specknets in more detail, discussing in 3.4.1 the research challenges in terms of their networking character and system requirements, and proposing in 3.4.2 a research map for specknets, followed by a study framework in 3.4.3 to enable investigation in the context of this thesis. Lastly, in section 3.5 a number of networking services that are used later on in the thesis are explained.

3.2 Wireless Sensor Networks

The past decade has seen the advent of a new multi-disciplinary research field, which explores the potential of a new technology known as WSNs. Recent advances in the technological areas of micro-electro-mechanical systems, digital electronics, wireless communications, and battery chemistry have enabled the development of exceptionally small devices that are low-cost, low-power, capable of sensing and communicating with each other. Such devices have been brought together to create information networks in order to provide an inexpensive computation linkage with the physical world, as envisioned by [103].

Initial research in WSNs was supported by the Defense Advanced Research Projects Agency (DARPA) which sponsored research projects on developing wireless integrated network sensors for military applications [22, 105]. However, the area soon evolved and a wide variety of civilian, sensor-network application domains emerged over the years. For the development of efficient systems, WSNs need a combination of a wide range of information technology expertise, including hardware design, networking, systems software development and application domain experts [33].

Wireless sensor networks pose unique challenges due to the limitations and requirements of the technology at the level of both the single node and the overall networked system. Additional issues are introduced by the varying characteristics and demands of different applications that make it difficult to define the design space of sensor networks [113]. As such, the challenges of the WSN field can be viewed from several different angles. Indeed, the literature offers various classification attempts of sensor networks, such as with regard to issues that influence communication [125] or considering the diverse nature of applications [113]. The research challenges of WSNs are discussed in section 3.4.1. Next are given the definition and role of WSNs.

3.2.1 Definition

A wireless sensor network is a large-scale collection of small devices that are spatially dispersed in the physical world and which together perform sensing of the environment. A number of requirements are suggested in the literature when defining WSNs [5, 33, 64, 85]. In general, there is an area of interest, one or more phenomena that the network is responsible for sensing. The deployment of the nodes across this area need not be carefully engineered. Their position may be random, especially when deployed outdoors at inaccessible terrains.

The individual nodes are inherently resource constrained, having limited power, computational and storage capacities. To compensate for these restrictions, the nodes combine their individual resources to perform tasks in a cooperative manner. As the energy is usually supplied by batteries, low power consumption becomes a requirement of great importance. The lifetime of the network is limited. Even when rechargeable solutions are used, it is challenging for the network to afford intense operation for extensive periods of time. Therefore, it is important to carefully balance the operation of the different components within the nodes as well as the interactions between them.

In a miniature sensor device, radio activity is significantly more power hungry than computation. For instance, [104] show that sending a single bit 100m by radio can consume the same energy as executing three thousand instructions. This indicates that there should be limited communication among sensor nodes, so that the trade-off between communication and computation favours the latter, less expensive, activity. Additional requirements related to communication are the interaction links between nodes and the power levels of their receptions. Contrary to traditional data networks, communication in WSNs is commonly based on broadcasting within the local network using various degrees of flooding due to their dense deployment. Multi-hop communication means that individuals nodes can keep their reception power low, which may also contribute to avoiding some of the signal propagation effects long-distance wireless communication exhibits.

3.2.2 Role

Distributed WSNs are typically responsible for sampling the local environment and transferring the collected measurements to devices that require this information. Nodes that supply sensory data are called *sources*. They have attached sensors which they use to capture readings for one or more physical factors, and report the results through wireless communication to the *sinks*. A sink usually is a base station, a device external to the sensor network that is interested in receiving data from the network. Real-world projects, however, have been using diverse configurations which do not necessarily correspond to the standard set up of multiple sensor nodes and a single, local, external base station. For example, the sink may be another sensor device within the network or simply a gateway that forwards the data to a different, larger network.

The role of a typical WSN is to obtain data about a physical phenomenon, disseminate this information to other nodes and, eventually, to the sink. Throughout this process the sensor nodes are responsible for sensing together with the first stages of processing the captured data. In some networks an additional task is introduced, that of performing appropriate actions based on observations derived from the sensory input. The literature refers to these type of networks as wireless sensor and actor/actuator networks (WSANs) [4, 57, 95, 132]. WSANs are considered an extension of WSNs, where *actors* or *actuators* are resource rich nodes, capable of controlling some physical object, for example a switch or a motor, or modifying system parameters.

3.3 Speckled Computing

3.3.1 Introduction

Speckled Computing [1] is an emergent branch of the WSN field that aims to create a new platform of sensing devices of minute dimensions, called *specks*. Each speck contains its own processor, memory, battery and communication hardware, and can be equipped with a variety of sensors. The research domain of Speckled Computing envisions a new generation of 'spray-on computers' in which dense networks consisting of thousands of specks, called *specknets*, can be created. Specks may be scattered on a person or surfaces, attached to rigid objects or even placed in flowing liquids, and act as a 'computational aura', opening up a wide variety of potential applications [143].

According to [139], research in Speckled Computing is shared between: the physical architecture of the speck which involves the resolution of technical issues, such as fabrication of the different parts of the speck device and their integration into a working unit; the specknet architecture which concentrates on the development of firmware and protocols necessary for the realisation of a distributed network of specks; the organisational and application-related challenges of designing and developing a new model of distributed, self-organising computation that must take into consideration specific requirements and limitations of the specknet technology.

Research in the field of Speckled Computing is still at an early stage. Design of the different subsystems that constitute a speck device, such as battery and radio technology, is under development [10]. In terms of the specknet architecture, Wong *et al.* have developed a class of low-power MAC protocols (SpeckMAC-D and SpeckMAC-B) [140, 141, 142]. Another contribution for specknet-based applications that require location information, is the proposal by McNally *et al.* [93, 94] of a distributed algorithm for logical location estimation of mobile

specks, which does not require use of expensive solutions such as global positioning system (GPS). For the specknet technology to mature, however, further issues require investigation, including specification of efficient identification techniques, communication protocols, and routing algorithms.

3.3.2 The Speck Device

A speck is designed to be an autonomous sensing device with renewable energy source, programmable and communication capabilities [139, 143]. Sensors allow the speck to capture data from the environment while in-built processing capabilities enable filtration of input data. Output information can then be used by attached actuators, such as motors, or components that provide direct feedback, such as LEDs.

Figure 3.1 shows ProSpeckz (Programmable Specks over Zigbee Radio), a prototype built with off-the-shelf components to serve as a test platform for development of specknet-based applications and for informing the design of miniature specks. The main components that constitute the ProSpeckz are:

- a computer-on-a-chip that combines a micro-processor and memory (FLASH and RAM),
- a radio chipset which is compatible with the IEEE 802.15.4 standard for low rate wireless personal area networks,
- an antenna that allows communication ranges from a few centimetres to over a few meters,
- a power supply, such as compact rechargeable batteries, and
- a number of sensors which vary depending on the application.

In the future, specks are intended to incorporate additional means of wireless communication (optics) and renewable energy (solar cells).

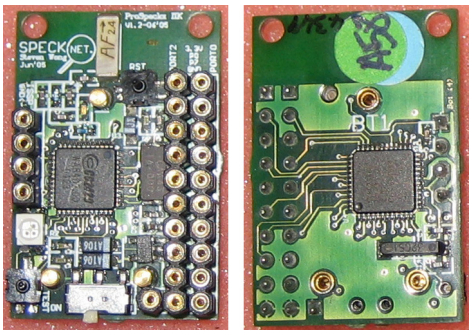


FIGURE 3.1: The speck prototype ProSpeckz IIK without battery (June 2005); dimensions 33 × 22 × 8 mm.

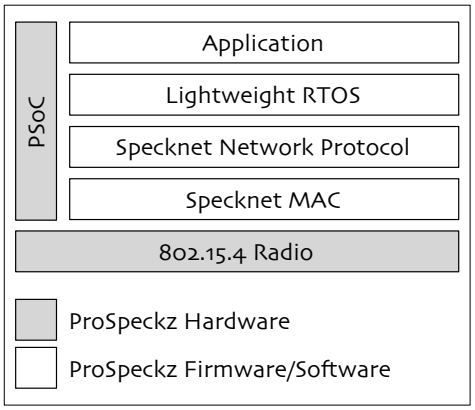


FIGURE 3.2: ProSpeckz system-level overview. Reproduced from [139].

The system-level overview of the ProSpeckz, illustrated in figure 3.2, reflects the hardware and firmware/software layers of the actual semiconductor speck. As mentioned in section 3.3.1, research is ongoing and all layers are under development, with the specknet MAC layer being among the first that has been examined in depth. In terms of application, so far ProSpeckz devices have been used in small scale network applications to demonstrate responsive environments (smart furniture, mood cloud) [143], implement jewellery networks in the domain of wearable computing [77], and create a distributed, wireless motion tracking system [148].

3.3.3 Specknet Limitations and Requirements

The specknet is intended to be a generic, fine-grained computation platform consisting of specks. Individually, specks are computationally weak. By joining a large number of specks together, however, the potential computational power of each speck increases as it is now part of a system that handles tasks collectively. Distributed functioning is enabled by incorporating wireless communication into the system. This allows specks to interact with each other and share the workload of data acquisition and processing. Interaction exists at yet another, higher, level between the specknet and the environment, in applications that require the

extracted information to be reported externally or to be used directly by the specknet in order to modify the environment.

The resource-constrained features of specks inevitably impose restrictions on the operation of the specknet and introduce unique networking requirements.

Limitations The minute dimensions of the speck device shape the design process of its constituent parts which, in turn, have an effect on the overall performance and efficiency of the specknet. Committing to a small size physically entails limited space for providing on board memory and power supply. Therefore, the storage capacity of specks is extremely limited (about less than 10 KBytes of FLASH memory and 1 KByte at most of RAM), and so is their energy. Processing power is also restricted, especially due to memory constraints, as physical size of processors is less of a concern (powerful 32-bit processors can be found at small dimensions of 0.5 mm^2).[1] In terms of energy, the most expensive activity in a speck is radio usage [139]. Radio data transmission and reception draw significant amounts of power. These tasks are, typically, more power-hungry than processor and sensor operations. Finally, radio communication between specks is of limited range and unreliable. To minimise the size of the antenna area (13×6 mm), operation is set at high frequencies (2.4 GHz) which, however, incur high path losses [137].

Requirements Perhaps the most critical challenge in specknets is to minimise power consumption at every design level [32]. Energy drain causes specks to become unavailable temporarily, that is until they gather sufficient energy from the environment to resume operation. Being one of the most power hungry operations in a wireless sensor device, radio communication is largely responsible for the energy drain. Specknets, thus, need to make use of lightweight, power-conscious communication protocols to balance out energy consumption. With

[1] Technical information was obtained via discussions with members of the Speckled Computing group.

respect to processing, limited individual capabilities along with the lack of base stations force specknets to operate in a decentralised manner, by distributing tasks among specks while encouraging collaboration. Lastly, specknets are vulnerable to failures due to the unreliability of wireless communication, such as loss of connectivity or conflicts during transmission, and harsh operating conditions when deployment takes place in an open environment with uncontrollable factors. To overcome such difficulties, specknets need to employ dynamic network protocols and algorithms to account for losses and inconsistencies in the organisation of the network, and exploit any population redundancy to minimise the impact of unpredictable speck deaths.

What has been described so far with regard to specknets does not seem to be substantially different to the description given about WSNs. Is there a difference between the two systems?

3.3.4 Specknets and WSNs: What Is the Difference?

In principle, there are no significant differences between the concept of a specknet and that of a wireless sensor network as it was envisioned originally by [48, 75, 103]. The main underlying objective is common: to create integrated, large-scale networks of low-cost wireless sensor devices which pervade the environment and perform distributed sensing and processing. An example which in many ways is similar to the Speckled Computing project is the Smart Dust project [135], one of the first research attempts to explore the idea of an autonomous sensing, computing and communication system that can be packed into a tiny cubic-millimetre computer.

As research progressed in the WSNs area, several platforms appeared in the literature [66, 133] which enabled designing, prototyping, and deploying sensor networks for specific applications. The Motes family [65, 102] is an example of such WSN technology which emerged from projects related to the Smart Dust project.

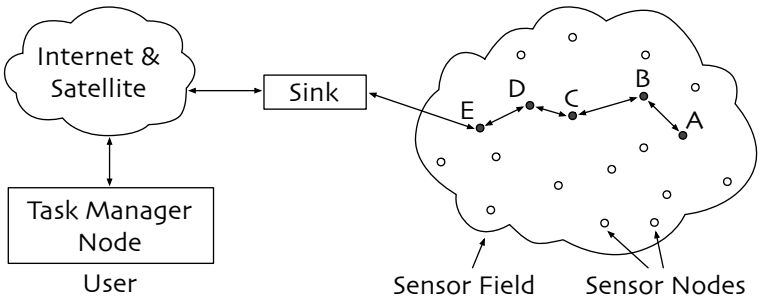


FIGURE 3.3: A WSN relaying information from a sensor field to a sink, ultimately destined to a user. Reproduced from [5].

The majority of WSN application-centric work, however, involves deployment of just a few sensor nodes compared to the thousands suggested initially [113]. Likewise, the first speck-based network applications use only a small number of the ProSpeckz devices, as mentioned in 3.3.2. This is not surprising, though, since the technical issues involved in developing miniature sensor nodes are not entirely resolved, hence the technologies are still evolving.

In terms of its role, a specknet is effectively closer to a WSAN rather than a WSN. The primary purpose of a typical WSN is to collect data from the environment and, then, relay this information to remote workstations for post-processing by other machines or end users, see figure 3.3. A specknet, on the other hand, is intended to perform in-network processing of the data gathered by the sensor specks and, if required, may produce a response based on the input observations affecting the environment. Thus, specknets differ to typical WSNs in that they assume no powerful station units which are responsible for gathering all sensed data, and they incorporate the additional layer of action that characterises the organisation of a WSAN.

3.4 Specknets

3.4.1 Research Challenges

As already mentioned, application-related research carried out in WSNs and Speckled Computing has mainly produced thus far prototypes or custom projects that target a wide range of application types. Because of the diverse nature of the application objectives, no typical structure or system architecture has been developed yet that is able to cover a set of basic goals, since these vary depending on the application. Nevertheless, there are attempts in the literature to classify existing applications and extract the common factors which appear to influence the design of WSNs [5, 41, 71, 76, 113, 116, 125, 147]. Below are listed some of the major aspects that have been identified in the literature to have a significant impact on the development of applications using the WSN and, consequently, specknet technology.

Network Characteristics

Deployment Installation of specks in the area of interest may be performed either by scattering the specks at random or by carefully engineering a deployment plan and manually placing each speck in the desired position. Deployment may happen only once at the beginning, or it can be repeated at any time while the network is functioning to replace dead specks or to extend the network with additional specks. Network properties that are affected by the method of deployment include the expected speck location and density, the expected network connectivity and, in general, the overall topology of the specknet.

Mobility A specknet may be entirely static, or may exhibit spatial mobility either throughout the whole of the network or involving only a subset of specks. When the cause of movement is a source external to the network,

for example water or wind, then mobility is considered an incidental effect of the surrounding environment. Otherwise, it is a property of the system and is further classified as passive when the specks have no control over their movement, for example in case of attachment to a mobile object, or active when the speck itself has automotive capabilities. Moreover, mobility can be of varying degree, constant or occasional. Mobility has a strong impact on the topology of a specknet, especially if the speed is high and this, in turn, influences the design of communication and routing protocols, and distributed algorithms.

Infrastructure This term is used to describe the supporting facilities which are necessary for network operation in terms of communication, localisation or time synchronisation [113, 147], or, more specifically in terms of communication, the protocol overhead needed to configure, maintain and optimise network operation [125].

According to the above, there are two classes of networks: the *infrastructure-based*, where, for example, specks are able to communicate directly only with base station devices which, in turn, must be able to communicate with each other or require GPS satellites for localisation; the *ad hoc*, where specks can communicate directly with each other, acting as routers or relays.

The latter description refers to the conceptual classification of communication within a specknet which can be categorised into: *application* communication, which relates to the transfer of sensed data to the sinks; *infrastructure* communication, which is required for keeping the network functional, ensuring robust operation in dynamic environments and optimising overall performance.

Network Topology The distance, in terms of communication links, between any two specks in a specknet in other words the maximum number of hops between any two specks in the network, defines the topology of that network. For example, a fully connected network where every speck is able to directly

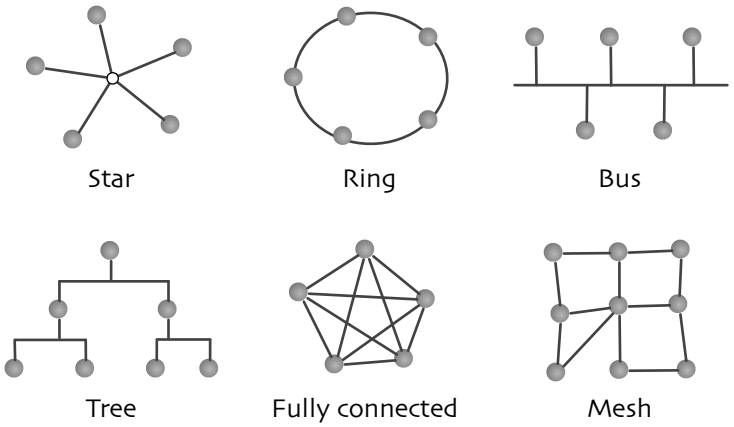


FIGURE 3.4: Basic network topologies. Reproduced from [85].

communicate with any other speck within the network is of the simplest, single-hop, topology. Other basic network topologies include a star network, for example an infrastructure-based network with a single base station, a mesh network where transmission is generally allowed only to a speck's nearest neighbours, a multi-hop network that forms an arbitrary graph. Figure 3.4 illustrates basic network topologies.

As already noted, network topology can be affected by speck mobility. However, even static specknets often have a dynamic topology due to specks joining or leaving the network. Population fluctuation can be caused by change in the specks': radio mode (for example when applying radio duty-cycling for power saving), available energy (energy depletion results in removal from the network), failure (physical destruction because of hostile environmental conditions). The topology, in turn, may affect other network characteristics, such as latency, robustness, capacity, and complexity of data routing and processing. For this reason, specknets require special communication protocols that take into account, potentially frequent, topology changes.

Density The density of a specknet is defined as the number of specks per unit area, and can vary significantly depending on the application requirements. Once again, speck mobility and population fluctuation may affect the density of a network over time and space. Furthermore, the density is not always

uniform throughout the network, especially in case of random deployment or passively non-static networks.

Coverage The coverage of a specknet measures the degree to which specks cover through their sensors the area of interest. Network coverage depends on the effective range of the sensors attached to the specks, and may vary across the network due to non-homogeneous density. Specknets with *sparse* coverage cover only parts of the area of interest, *dense* coverage is more likely to completely cover the area of interest, and *redundant* coverage means that the same physical location is sensed by multiple specks. The higher the density the greater the network coverage becomes, which can have positive impact on the robustness of the network and may also allow for the development of power-saving sleep schemes that exploit the redundancy in specks.

Connectivity The connectivity of a specknet is determined by the communication ranges and the physical locations of individual specks. A network wherein there is always a communication path between any two specks, either over single or multiple hops, is called *connected*. If the network is occasionally partitioned, then connectivity becomes *intermittent*. When specks are isolated most of the time and become connected only occasionally, then the connectivity of the network is *sporadic*. Connectivity affects the design of communication protocols and methods of handling data.

System Requirements

Addressing In specknets, addressing may be needed for various networking and application purposes, such as communication and routing protocols or data tagging. The traditional technique of assigning unique identifiers to individual specks is considered wasteful. Besides requiring large address size, a strict per-speck addressing policy becomes inefficient in a network where it is unlikely that any two specks would need to communicate with each other.

Furthermore, off-the-shelf sensor nodes are typically not pre-programmed with globally unique addresses. Thus, networking and application mechanisms may dynamically allocate unique identifiers or dismiss per-speck address-based techniques altogether.

Lifetime The desired lifetime of a specknet depends on the application and may vary from a few hours to several years. There is no standard definition of lifetime. Again depending on the application, the end of a specknet's lifetime may be signified by the first speck failure or a fixed ratio of specks having failed due, for example, to energy expenditure. For a fully connected network, lifetime may mean the time until the network becomes disconnected in two or more partitions. In terms of coverage, lifetime may indicate the time when a point in the area of interest is no longer observed by any specks for the first time. In any case, the lifetime of a specknet usually requires an energy-efficient way of operation which, however, has a trade-off against quality of service, as investing more energy can increase quality but decrease lifetime.

Scalability Large-scale specknets introduce scalability requirements with respect to the network architecture, protocols and algorithms. The employed methods must be able to work with large numbers of specks and exploit the potential high node density that specknets are expected to have in many cases. Additionally, limiting the state maintained by each speck during protocol processing to local information only, for example relating to specks within communication range, can help a network scale without needing to accumulate additional information as the size of the network increases.

Quality of Service The quality of service requirements for a specknet greatly depends on the type of application the network is designed for. Traditional requirements such as bounded delay or minimum bandwidth, usually found in multimedia-type applications, are considered irrelevant in the context of specknets where occasional delivery of data may be sufficient. However,

delay may be critical in cases where the network is responsible for controlling actuators. In other cases, real-time constraints may apply, for instance, when the network must report a detected event within a certain period of time. Perhaps, the most important aspect in specknets is the quality of information that the network can provide, taking also energy into account.

Reliability The issue of reliability or fault tolerance is prevalent in specknets due to the nature of the system. Specks may run out of energy, become damaged or permanently lose connectivity from the rest of the network. In such cases of failure, the ability of the network to remain operational without significant interruption indicates the level of robustness of the system. Demands for reliability in a specknet differ depending on the application. For example, the fault tolerance requirements may be more relaxed in a scenario where a specknet is deployed in a house to monitor humidity and temperature levels, compared to an outdoors deployment for fire detection. To tolerate speck failure, an obvious suggestion is to try to exploit redundancy, that is, use more specks than would be necessary if all specks functioned properly, so as to ensure each speck has several alternatives for sustaining its functionalities in case a neighbouring speck fails.

Security Compared to other architectural aspects, research on the security challenges of WSNs and specknets has been limited. Specknets face security issues similar to those of conventional networks, such as key establishment, secrecy and authentication, or robustness to communication in case of denial-of-service attacks. However, severe resource constraints and close interaction with the physical environment render traditional security techniques inadequate in the context of specknets. Furthermore, unique problems arise from the very nature of specknets, such as node-capture attacks or physical tampering, which stem from their deployment in open environments and accessible locations. Another challenge with respect to system design is to

integrate security into every component of the system's architecture, rather than treat it separately as a standalone component.

Auto-Configuration An important system requirement for specknets is the ability to carry out autonomously as many of the necessary configuration tasks as possible. The large number of specks along with their installation at potentially hazardous and dynamic environments require that the network does not entirely rely on pre-configured operational parameters or external means of configuration. Moreover, the topology of the network is most likely going to change after initial deployment with specks failing and disappearing from the system or new specks joining in. In such circumstances, the specknet should be expected to adjust by reconfiguring itself so that it continues to function as expected without compromises.

Collaboration A network of specks is regarded as an inherently cooperative system. Single specks have similar individual goals but, most importantly, share common, system-wide objectives, such as collating information from the sensors across the network or balancing the communication load among all specks in the network. In order to achieve these network-level objectives, specks are required to combine their individual resources and work together instead of competing with each other.

3.4.2 A Research Map

Having reviewed the literature on specknets, it is now possible to propose a research map for specknets, illustrated in figure 3.5. A specknet can be examined at two different scales: the scale of a *single speck*, where issues concerning the individual device are involved, and the *systemic* scale, where issues with regard to the overall network are included. Furthermore, issues that pertain to each scale can be grouped into two broad categories: those relevant to *behavioural* aspects of the individual device or network, and those concerning *technical* details of the

corresponding scale. Given the system-level overview of ProSpeckz in figure 3.2, what is referred to as 'behavioural aspects' here is associated with the application level, whereas the remaining levels compose the technical side of the system.

The broader area of WSNs lacks a characteristic system architecture, see section 3.4.1. A modified version of the standard OSI reference model is sometimes used by the literature to outline the types of algorithms and protocols that can be found in WSNs [5, 76], [41, p. 99]. The first four layers of the OSI model, that is the *physical*, *data link*, *network* and *transport* layers, along with the *application* layer summarise the main organisational structure used in WSN research which, by extension, apply to specknets too. Similarly to the ProSpeckz system-level overview, the behavioural aspects of specknets are mostly pertinent to the application layer, while the remaining four layers are linked with the technical characteristics of the system.

An AIS practitioner can approach the specknet in several ways. As mentioned in section 3.2, the WSN research community combines several different areas of expertise that span from radio engineering to application-specific exploration. While understanding of how the overall system operates is important, in-depth knowledge of the particulars from all aspects involved at each scale is difficult to have. Therefore, depending on the research topic of interest, certain aspects of the system can, at least initially, be treated as a black box. For example, if the interest lies in a specific application problem, then the AIS researcher can focus on studying the behavioural aspects of the system, employing existing solutions from the WSN field to deal with technical matters. In like manner, if the focus lies on some technical aspect of the system, application-end behavioural issues can be of lesser concern.

As might be expected, the distinction between behavioural and technical aspects, and similarly, between the related layers mentioned above is far from definite. For decisions made on the technical side or some low layer may impact behavioural issues or the layers above. Conversely, requirements of behavioural nature or

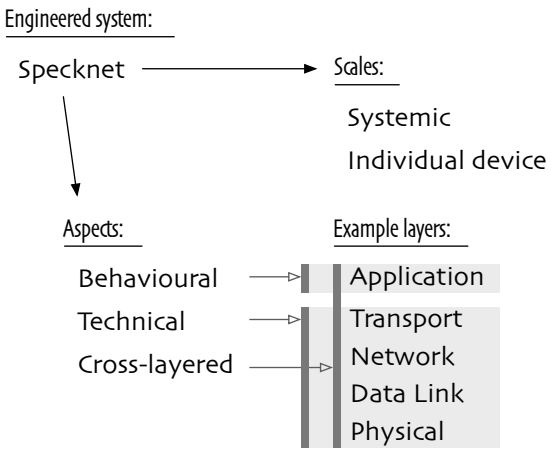


FIGURE 3.5: A research map for specknets.

of layers high in the stack may pose restrictions on technical issues or the lower layers. For these reasons, there is always the additional option of approaching the system in a cross-layered manner, where issues across both aspects or multiple layers are explored jointly.

In the case of this thesis, specknets are primarily considered from a *systemic* point of view and, when examined against the immune system, the focus is mainly on the *behavioural* aspects of the engineered system. Nonetheless, section 3.5 presents a discussion on certain technical aspects related to a number of networking services necessary for the specknet implementation of chapter 6.

3.4.3 A Study Framework

This section proposes a framework of study for specknets to enable investigation within the context of this thesis. The suggested framework, shown in figure 3.6, assumes a generic cycle of operation for a specknet, broken down into a number of components. Any input captured by the specknet, whether related to the environment or the network itself, is described by the data collection component. For example, a specknet may collect sensor data of environmental phenomena,

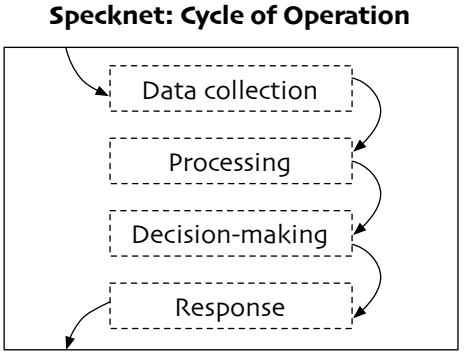


FIGURE 3.6: A study framework for specknets that outlines a generic logical cycle of operation of the system.

data that describe the state of speck devices, or data related to specific network functions, such as protocols of communication or routing.

Collected data are fed into the next component of processing. For example, sensor data may be filtered to reduce noise, or device-related data may be integrated with protocol-related data to generate information describing the impact of the way traffic is routed on the energy consumption of specks. The extracted information is then piped to the decision-making component for further integration. This involves processes such as voting, classification or learning performed by individual or groups of specks. The output is the course of action that should be taken.

The last component in the cycle represents the response of the specknet, and involves the execution of the decision passed from the previous component. A response may require specific actions or to remain in the current state for the time being. The cycle resumes with the acquisition of additional data and repeats so long as the specknet is up and running.

It is important to note that the proposed study framework presents the operation of a specknet as a collection of abstract functions following a logical sequence. This sequence is not intended to imply any assumptions about how the function of a specknet is managed internally. In other words, the cycle of operation described does not necessarily translate to a uniform way of operation across the network,

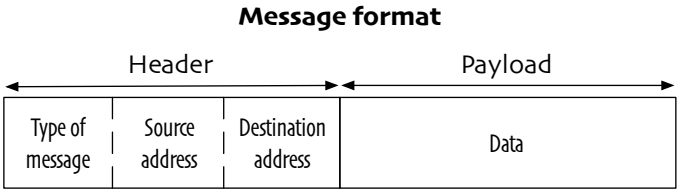


FIGURE 3.7: General format of a radio message in networking.

where all specks enter and exit each component in a synchronised manner. The actual organisation of a specknet may range from synchronous setups to more complex configurations of the functions of the components.

3.5 Networking Services

In order to implement the specknet system of chapter 6, the following networking services must be considered: addressing, neighbourhood and routing. First, though, a note on the general format of a radio message, the basic communication unit of such services. A message consists typically of two basic parts, a header and a payload. The fields that constitute each part vary depending on which networking layer the message is processed at. In general, the header contains the type of the message and the addresses of the sender and intended receiver, whereas the payload holds the data bytes, illustrated in figure 3.7.

Addressing

In WSNs unicast communication is achieved with the use of addressing protocols, which guarantee the assignment of locally or globally unique identifiers to nodes. Addressing algorithms for WSNs may require central or distributed maintenance of one or more allocation tables, or may rely on conflict detection procedures to resolve address conflicts. The former approach tends to ensure globally unique identifiers, as opposed to the latter which is used more as a local solution. A survey on addressing protocols for WSNs can be found in [145].

Neighbourhood

Neighbourhood formation is a basic networking mechanism for WSNs that enables a node to have a view of the logical state of nearby nodes by exchanging messages containing state information. Neighbourhoods involve maintenance of a table of neighbour states by each node. It can be established in a number of ways, for example, using acknowledgement message protocols, proactive regular updates, or transmitting a node's state as part of normal data communication.

Routing

A routing protocol is necessary to guide data messages towards the sinks. Main categories of routing protocols developed for WSNs include hierarchical and data-centric protocols. Hierarchical routing protocols are cluster-based, that is, they group nodes in such a manner so that data are efficiently relayed from source to destination. Data-centric protocols, in general, rely on queries sent out by the sink asking for data with specific properties, for example coming from a certain region of the network or describing a certain type of event. A survey on routing protocols for WSNs can be found in [3].

3.6 Conclusion

This chapter has introduced WSNs and specknets, and discussed the research challenges associated with these engineered systems. In addition, it has proposed a research map and a study framework for specknets, and explained certain networking services used later on in the thesis. The next chapter starts with describing the methodology followed in this thesis and continues with bringing together the immune system and the specknet in a parallel study at a systems level. This is followed by an exploration of the immune system, in terms of theoretical context and at the biological level, with reference to specknets.

Chapter 4

Synthesis and Focus

4.1 Introduction

Having introduced the two complex systems under study, the immune system in chapter 2 and the WSNs in chapter 3, this chapter continues with the parallel investigation between the two systems in the context of AISs. The methodology followed is illustrated in figure 4.1. The first step calls for studying how the two systems correlate with each other. This is presented in section 4.2, where the two systems are examined in terms of their structure and organisation.

The next three steps in the methodology deal with narrowing the focus of the investigation with relation to the immune system. These are covered in the remainder of this chapter. In particular, step two concerns the theory adopted to help interpret immunological functionality, whereas steps three and four refer to the specific immunological concepts and elements to be identified at the theoretical and biological levels respectively. Section 4.3 presents the cognitive immune paradigm, explaining the reasons for choosing this particular theory and analysing in what way the cognitive immune system (CIS) relates to specknets. Sections 4.4 and 4.5 cover the theoretical and immunobiological reference points

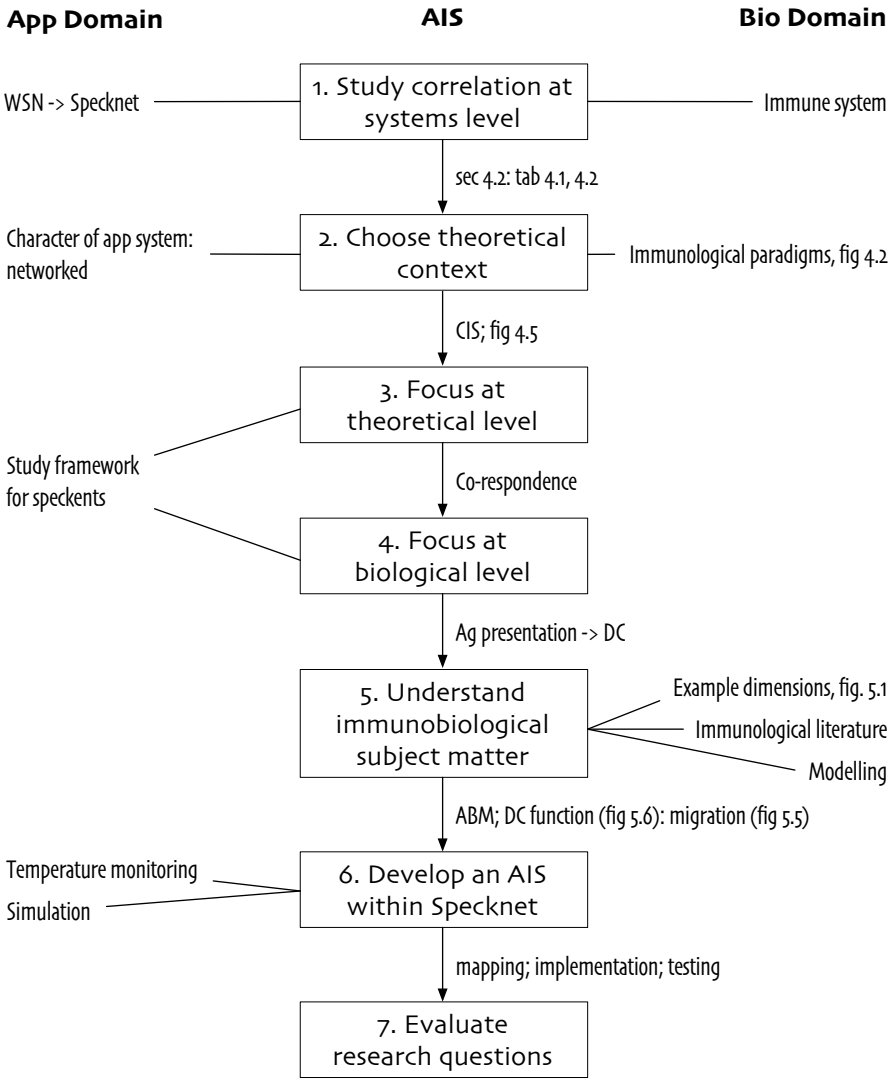


FIGURE 4.1: Methodology followed in this thesis.

of investigation respectively, biased by the study framework for specknets of figure 3.6. Where appropriate, the results of the decisions made are discussed with respect to the current AIS literature.

The fifth step of the methodology involves exploring the elements of focus in order to learn more about their functionality and understand their behaviour. This is done in chapter 5 by examining the relevant immunobiological literature and by undertaking a modelling exercise in an agent-based environment based on the life cycle of a dendritic cell.

The sixth step investigates the development of an AIS within a specknet environment, which is the subject of chapter 6. The methodology concludes with evaluating the thesis research questions from section 1.1, taking into consideration the results from all previous steps. This last step is covered in chapter 7.

4.2 Correlation between Specknet and Immune System

4.2.1 Structural Attributes

In the first instance, the specknet and the immune system appear to have similarities in terms of structural system attributes. In addition, the immune system exhibits on a functional level network properties that are desirable by specknets. To recapitulate what has been discussed about specknets in chapter 3, a specknet is a large-size collection of very small devices, called specks, intended to be a generic platform for ubiquitous computing. Networks of specks are envisioned to operate as stand-alone systems with distributed control mechanisms that allow for the in situ sensing and processing of environmental information, and call for action subject to the type of application, all performed in a collaborative manner.

Considering the immune system from a network perspective, examined in section 2.2.2, several common features become apparent between the immune system and the specknet with respect to their structure and organisation. First, both systems include large populations of agents that are distributed in their respective environment. In the specknet, specks are expected to be spread out in the area of interest, on surfaces or within objects, in positions not necessarily prearranged and which may change after initial deployment. In the immune system, some immune components occupy fixed, yet, distributed throughout the human body places, such as lymphoid organs, while other immune elements circulate around

Specknet	Immune System
Great number of specks	Large populations of immune agents
Specks dispersed in the environment	Immune elements distributed within the body
Specks basic and unreliable	Immune agents simple and expendable
Networking via wireless communication	Interacting via molecular shape and chemical signalling
No single coordinating base unit	No central organ or external control

TABLE 4.1: Comparable system attributes between the specknet and the immune system.

the lymphoid organs and body tissues achieving function in mass numbers, such as leukocytes.

Although single immune cells and molecules are expendable for the immune function and relatively simple units when compared to the overall system, collectively they manage to build up effective immune networks by deploying nonlinear connections, basing their interactions on molecular shape matching and chemical signalling. Likewise, individual specks are regarded as weak and unreliable components on their own, since they are equipped with only basic functionality and bear modest resources. Within a specknet, however, wireless communication enables these dispersed units to bring their capabilities together and join their minimal resources to fulfil the required application goals.

The organisation of a specknet involves no base unit as part of the network that might be responsible for globally coordinating participative specks. Instead, a specknet is designed to operate in a decentralised fashion by relying on specks themselves to carry out the necessary tasks cooperatively. Similarly, the immune system relies on self-regulatory mechanisms and processes, without any central organ guiding immune function or any outside source of control. Table 4.1 summarises the system attributes examined so far for the specknet and the immune system.

4.2.2 High-Level Properties of the Immune System

With regard to the high-level properties that the immune system exhibits from a computational point of view, there are several features on a functional level that would be ideal for a specknet to manifest. From reviewing the challenges of specknets, presented in section 3.4.1, questions arise such as: how to program a specknet so that the interactions of many autonomous, spatially distributed, specks may result in coherent global behaviours? Is there any way to develop scalable solutions? In this regard, the immune system has several mechanisms with excellent self-organising qualities to showcase, as discussed in chapter 2, though these are not entirely understood yet in a networking context.

Another important question is: how to deal with unreliability of individual specks? Installation of specknets at turbulent sites subjects them to harsh operating conditions which may damage part of the network. Hardware faults, for example sensor malfunction, may feed the network with inaccurate data about the environment. Security issues, such as node capture, may compromise the integrity of the network's information, or impair part of its function. Lack of power means node losses which may cause significant areas of the network to become partitioned or disappear. Situations similar to these are handled by the immune system which is able to accommodate error and missing elements, but also provide multiple response options in a flexible and conditional manner.

Moreover, how can a specknet cope with changes within the network? For instance, what mechanisms are required to manage additional resources, for example to incorporate more specks into the network in order to increase processing power and memory for sharing the work load, or to extend its data input points? What processes may allow the specknet to expand its capabilities, for example to accept new kinds of sensor and, then, learn to handle the newly provided information, or to reassign its focus to new tasks? Again, in cases that involve issues similar in concept to the above, the immune system proves to be a highly dynamic system, capable of adapting to change and of learning.

Property		Description
		The immune system:
Self-organisation	→	spontaneously arranges immune elements to form useful immune responses
Scalability	→	is able to deploy responses proportional to the severity of the situation
Resiliency	→	develops responses in a robust yet flexible way, withstanding error and missing elements
Adaptation	→	is capable of learning, and adjusting to unknown situations
Maintainability	→	keeps in good condition both itself and its host

TABLE 4.2: High-level immune properties that match some of the requirements of specknets.

Ultimately the specknet has to maintain itself. How can it achieve that while operating using decentralised control? What mechanisms can enable specks to monitor their own health as well as the health of the entire network, to perform their tasks in a cost-effective, in terms of energy, way, to know when to trade quality for gaining points in sustainability? The immune system faces similar issues that involve maintenance of stability of both itself and the host. Only it does this using highly inefficient techniques and relying on inexhaustible supply of immune agents. This is a point of mismatch between the specknet and the immune system, since the former is far from having unlimited resources available. On the contrary, specks need to strive for a balance between efficiently controlling their constrained resources and effectively performing their tasks.

A summary of the high-level immune features that match some of the functional requirements of specknets is given in table 4.2.

4.3 Selection of an Immune Paradigm

This section identifies what theoretical context is better suited for probing the immune system in the context of the specknet case study, see figure 4.2. To remind,

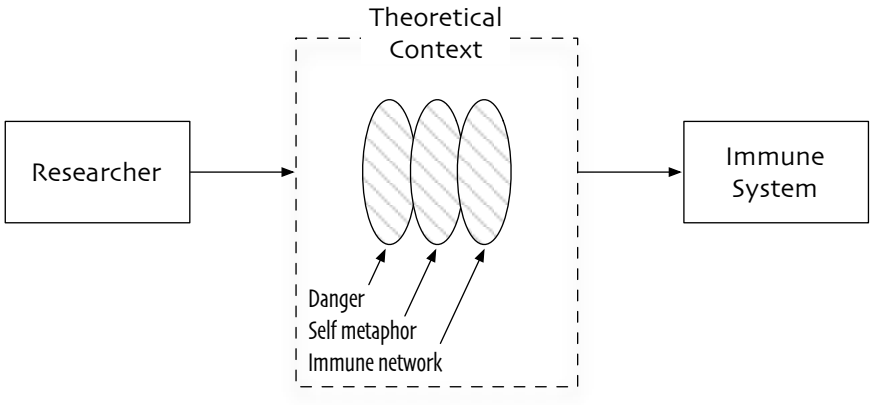


FIGURE 4.2: Example immunological theories for approaching the immune system.

section 2.3 discusses the fundamental conceptions of immunity that appear to be driving immunological thinking. These form a spectrum with the self-non-self discrimination and the immune network perspective on either end. Admittedly, no argument can be made with respect to the 'rightness' of either choice in terms of pure research interest. However, if examined with reference to the expectation of fully exploring the correlation points between the specknet and the immune system, examined in the previous section, then there is a difference between the two approaches.

A network-based approach offers a wider view of the immune function and matches the specifications of the specknet better than a perception which assigns a specific role to the immune system, such as discrimination or protection. In this regard, a *networked* paradigm is deemed appropriate for probing the immune system in the case of this thesis. Specifically, the cognitive view by Cohen [25, 26] is adopted, as it appears to be one of the most complete contemporary paradigms that have been proposed within immunology. The cognitive paradigm offers a holistic view of the immune function with an emphasis on the complex interactions that occur within the immune network, suggesting that through its activity maintenance of the body is achieved.

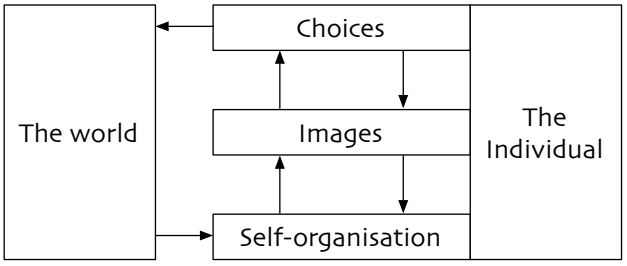


FIGURE 4.3: Elements of cognition. Reproduced from [27].

4.3.1 Cohen's Cognitive Paradigm

In [27, p. 92], Cohen defines a *cognitive system* as one that integrates three attributes, see figure 4.3: it creates internal *images* of the world within which it exists; it *self-organises* by using experience to build and update its internal images; it is able to make *decisions* by choosing among alternatives. According to Cohen [27, p. 124], these elements of cognition are central to the strategy of the immune system which consists of three parts: *recognition*, sense signals and respond to them; *cognition*, interpret input signals, evaluate results and make decisions; *action*, execute decisions.

In this cognitive view, the immune system is regarded as a system that provides services of *maintenance* to the functioning body, a role broader than, but still covering, protection. Immune maintenance involves several activities, including cell growth and replication, cell death, movement and differentiation, and functions that modify tissue support and supply systems [27, p. 118]. These effects are caused by actions of immune *agents* on the body, that is by immune *cells* and *molecules*. However, for the immune system to be fully appreciated, additional characteristics need to be considered besides the agents that perform immune tasks. Further important aspects of the immune function are the *arrangement* of the immune agents *in anatomical space*, and their *interactions in time* [27, p. 103].

In order to achieve effective behaviour, the immune system is required to generate specificity out of non-specific properties. This situation challenges the concept

of one-to-one relationship between cause and effect, typically found in immunological models that follow the 'self' metaphor. As already noted in section 2.2.1, immune cells sense signals via receptors, molecules that are usually found on their surface, which relay the signal into the cell [27, p. 111]. An input signal is another molecule, termed *ligand*, which is said to be bound by an immune cell's receptor, such as an antigen. Properties that refute an exclusive one-to-one interaction between receptors and ligands include: *degeneracy*, any receptor may bind more than one ligand, and vice versa [27, p. 138]; *pleiotropia*, a single agent has the capacity to produce diverse effects [27, p. 141]; *redundancy*, several agents may produce the same effect [27, p. 142].

Therefore, Cohen asserts, since immune specificity cannot be reduced to chemical specificity, it must be contrived by immune physiology [27, p. 148]. Two important immune properties that contribute to the emergence of immune specificity, and from which immune cognition arises, are: the different immune agents perceive different features of the molecular world; and, the agents mutually cooperate to form regulatory networks [27, p. 149]. A key process that forms the basis of immune specificity is *co-respondence*: the mutual exchange of signals between immune agents occurring in response not only to the target entities in need of immune maintenance or protection, but also to the response of fellow agents to different features of these target entities [27, p. 159].

The process of co-respondence is dependent on *immune networks* that involve: interactions between immune molecules produced from both immune and tissue cells, such as cytokine networks [27, p. 162]; interactions between immune cells themselves, such as idiotypic networks [27, p. 164]; anatomical networks which help bring physically together the different immune agents [27, p. 165]. In this regard, Cohen [27, p. 165] defines a *network* to be:

> . . . a system in which the components are connected to each other such that a change in the state of one component can have some effect on the states or connections of the other components.

Considering the diversity of immune agents and the entire array of their potential positive or negative effects, and multiplying their interaction points by the degrees of degeneracy in signalling and the pleiotropism in response, the complexity of the networks that comprise the immune system becomes apparent.

With regard to the dynamic aspect of the immune function, the interactions of immune agents in time reveal that the operation of the immune system is an *ongoing* process of self-organisation [27, p. 166]. Immune self-organisation [27, p. 172] is one of the three elements that define immune cognition, indicating the progressive creation of information via learning and memory that happens across two scales: the innate *germ-line* history of the species, and the adaptive *somatic* experience of the individual [27, p. 103]. The second cognitive element, that of creating images of the individual's internal and external environments, is performed by the immune system at various levels: concrete, immune receptors provide physical negative images of the ligands they bind; abstract, interacting entities form process images which, for instance, may delineate a certain process of immune reaction; distributed patterns of various immune molecules or cells exist throughout the body [27, p. 174]. Decision-making, the final element of immune cognition, is determined by the interactions of immune agents, that is the molecular dialogue that associates somatic perceptions with germ-line classes of behaviour [27, p. 181] in order to choose a particular type of response.

4.3.2 Cohen within AISs

Before expanding on Cohen's viewpoint further, the AIS literature is examined for works that consider the cognitive immune paradigm. Although Cohen first proposed the cognitive paradigm in the early nineties [25, 26], it was not until after the publication of a book in 2000 [27] explaining in depth the theory of a cognitive immune system that this viewpoint started to become noticed within the field of AISs.

The first appearance of Cohen's theory in an AIS publication seems to be in the paper by Andrews and Timmis [8], reviewed in section 2.3.2, as an example suggestion to motivate new sources of inspiration for the future development of artificial immune systems. The authors single out the idea of receptor degeneracy as a candidate for AIS inspiration, an idea related to immune recognition and specificity. The authors observe that the majority of past AIS algorithmic approaches, that utilise the concept of receptor-antigen binding in recognition systems, deploy a one-to-one mapping relationship, typically implementing a monolithic matching between detectors (or receptors) and antigens. However, according to the concept of receptor degeneracy, recognition starts at the molecular level, where a usually partial binding site forms between a receptor and a ligand. The concept extends to the scale of immune agent populations to explain how a population of degenerate receptors may render recognition specific via the organisation of collective patterns.[1] The degeneracy concept is further explored by the authors in subsequent publications [9, 96] via computational modelling of cell agents that bear degenerate detectors, interacting with antigen agents.

Owens et al. [99] consider Cohen's theory in a position paper that discusses the role which the immune system can play in providing inspiration for the development of homeostatic engineered systems. The authors sketch an architecture for homeostasis for use in electronic systems. They suggest the property of homeostasis in artificial systems, such as robots, can be linked with a control system that is responsible for maintaining functionality of the system at various levels, from physical components to completion of tasks. Analogies are drawn between such a homeostatic control system and the immune system. These fit Cohen's suggestion on the kind of strategy employed by the immune system to provide maintenance to a functioning body.

Voigt et al. [134] examine the cognitive immune system alongside a classic learning classifier system, a machine learning paradigm introduced by Holland. The

[1] Details on the subject can be found in Cohen [27, p. 125–140, 174–181].

authors present the outline of a computational model of Cohen's immune theory, using the structure and internal mechanisms of the classic learning classifier as a starting point. They first introduce the concepts and representations required by the model, which include distinct sets of cytokines and actions, and a hybrid immune cell type that integrates the different classes of immune cells. The interactions and dynamics between the elements of the cognitive immune system are examined next, followed by the implementation of evolutionary mechanisms that are used for adapting system behaviour. The resulting model is presented as a computation loop, which reportedly is promising for use in the domain of machine learning and problem solving.

4.3.3 More on the Cognitive Immune System

Cohen has portrayed the cognitive paradigm from various angles. For instance, in [12], stimulated by information theory, he discusses the CIS as an information processing system with unique characteristics, such as creation of information and meaning, and sketches out a language metaphor. In [28, 31] he presents the CIS as a complex reactive system, and discusses the importance of emergence when attempting to explain such complex biological systems. In [29, 30], he draws a parallel between the CIS and the universal Turing machine, and proposes immune computation. Each of these angles help to better understand the cognitive viewpoint and, thus, are presented in the following paragraphs.

Informational View and the Language Metaphor

Using as a starting point the information theory developed by Shannon, Atlan and Cohen [12] attempt to place the immune system into an informational framework. According to the authors, biological information is carried by the DNA which exists within living cells. In the case of the immune system, the fundamental unit of information is an *antigen receptor* which exists in multiple copies on the

surface of a lymphocyte, such as a T cell or a B cell. It can also be found in soluble form, as an antibody produced by a B cell. Antigen receptors supply the immune system with a diverse set of (partial) negative images of antigens and, upon sensing their cognate antigen, signal immune cells to act.

Immune information is generated randomly, that is, the unique specificity of the antigen receptors that each lymphocyte clone has, is created by random or near-random processes. The potential number of different antigen receptors that the human immune system can generate is incredibly large (between 10^{10}–10^{15}), difficult to manage and inefficient to fully produce. Therefore, the way the immune system deals with its information is to produce an initial collection of random antigen receptors (primordial repertoire), which is shaped into a useful repertoire with the help of various processes. These processes occur at different stages of the individual's lifetime, and include: the deletion from the system of unwanted information, e.g. via the rejection of T cells during their development in the thymus; the replication of existing information, e.g. via the proliferation of B cells after their activation; the creation of new information, e.g. via the mutation that occurs on B cell clones during affinity maturation.[2]

In a sense, the information carried by antigen receptors is shared by the antigens they recognise. Although the information content of an antigen is intrinsic, its meaning is extrinsic and is defined by the type of response that follows its perception. In this regard, besides the repertoire of receptors, the immune system also has a repertoire of responses. From the viewpoint of self-non-self discrimination, the source of the meaning of any antigen depends on whether the antigen belongs to the self or not, and the immune response that follows an antigen's stimulus is seen as a reflex. From the viewpoint of the cognitive paradigm, though, the meaning of an antigen is created by the immune system itself, that is, an immune interpretation takes place via the internal processing of information about the antigen, which leads to the development of a particular type of immune response.

[2]Affinity maturation is a selection process which B cells undergo in response to antigen conformation [27, p. 169].

To perform the necessary information integration, the cognitive immune system organises itself by combining innate immunity with adaptive recognition of antigens. In the context of a language metaphor, the antigen serves like the subject of the immune sentence, and the context of germ-line ancillary signals in which the antigen is embedded are like the predicate. The particular response that is chosen from the response repertoire, thus, arises as a reaction, not to antigens, but to abstractions of antigens-in-context.

Complex Reactive System

In another attempt to explain how the immune system performs its cognitive decision-making process, Cohen [28, 31] borrows an example from the systems development literature, the transformational vs. reactive systems [58]. Transformational systems, in general, perform input/output operations. Under this definition, the defensive aspect of the immune system would be seen as the function of transforming the antigen and its context into a specific immune response by following a sequential procedure of discrete decisions based on a chain of discrete signals. A reactive system, on the other hand, continuously responds in parallel to many concurrent inputs using additional data beyond its input values, such as the timing of the inputs or the order in which they arrive. Cohen believes that the immune system behaves as a reactive system, being continuously active and making its decisions by simultaneously reacting to numerous, sometimes even conflicting, incoming signals.

It is suggested in [31] that a defining characteristic of a complex reactive system is the expression of emergent properties. Although regarded as a difficult concept to define in biological terms, it is advocated that emergence is a matter of scale. For the emergent properties of the immune system to be observed, and indeed of any complex biological system, examination at more than one scale is required. What is seen as interactions at one scale may be creating an object with distinct behaviour at a higher scale. For example, molecular interactions give rise to a

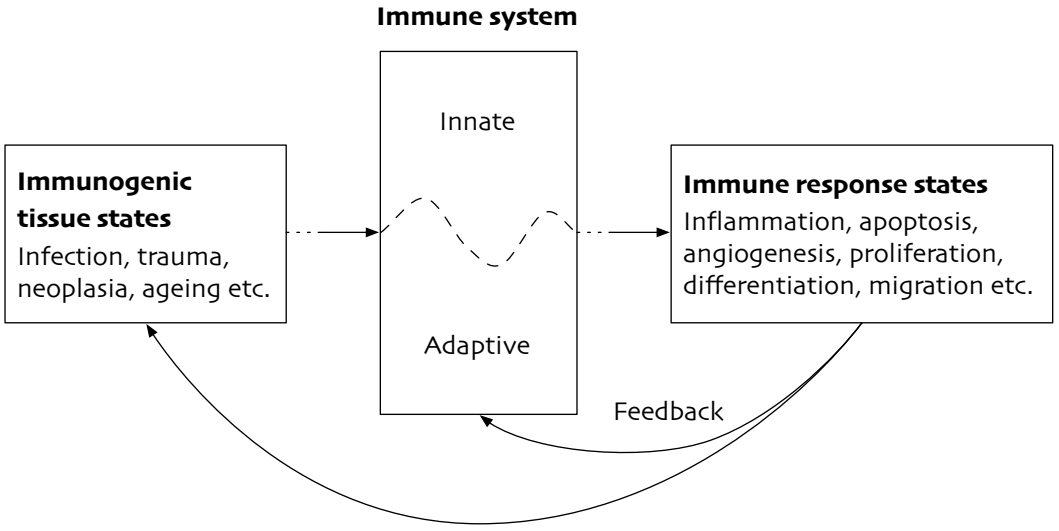


FIGURE 4.4: Immune computation, proposed by Cohen. Reproduced from [30].

higher-scale cell object, cellular interactions create higher-scale organs, and so forth. When viewing the immune system as a whole, this transition from interactions to new objects between different scales should not mislead the observer to consider that immune function is of transformational nature. Internally, the immune system behaves in a reactive way.

Immune Computation

Considering the CIS in computational terms, Cohen [29, 30] expands the description of a continuously reactive system to include the idea of immune computation. Starting from the basic definition of computation as the transformation of input data into output data according to a set of rules, Cohen proposes that the immune system translates the state of the body (input) into a fitting healing process (output). In this regard, Cohen notes that immune computation relates to the resulting behaviour of the immune system and not to its component parts. From an emergent perspective, however, biological computation occurs across multiple scales, at the scale of a single immune cell to the scale of groups of cells comprising the immune system.

Figure 4.4 illustrates the concept of immune computation. Input data to the immune system are provided by the body. These involve the conditions and molecular signals that affect or stimulate the immune system (immunogenic tissue states). Output data refer to the varied responses of the immune system. These range from restorative inflammation to defence against pathogens (immune response states). This computational process of translation between different types of states is iterative and continuous. In addition, the immune activities that ensue from the translation process feed back to both the body and the immune system itself, that is they modify the state of the body's tissues (e.g. healing) and also change the structure and behaviour of both the innate and adaptive arms (e.g. memory).

The set of rules for executing a basic computation can take the form of an algorithm. In the case of the immune system, a clear analogy of what distinct rules mediate the transformation of states is hard to completely specify. Instead, Cohen [29] suggests that "immune computation emerges from the parallel processing of information." Each immune cell can be mapped to a single processor which can be thought to collect input by its receptors and translate that into output by its secretions and behaviours. The immune system consists of hundreds of millions of individual cells working in parallel, the integration of which carries out the immune computation. Yet, as mentioned earlier, Cohen [30] notes elsewhere that "when referring to immune computation the view is synthetic rather than analytical: we look to the end behaviour of the system and not at its component parts." This seeming inconsistency in the concept of immune computation might be resolved if emergence is considered from Bedau's perspective, according to which emergent phenomena are somehow both dependent on and autonomous from underlying processes [14].

Returning to the discussion of immune parallel processing, the integration of individual cells relies on the networked organisation of the immune system. As

Specknet	Cognitive Immune System
Of high temporal and spatial complexity	Complex reactive system
Sustainability of application-end and network objectives	Maintenance of functioning body and regulation of immune activities
Ongoing operation	Continuous function
Collect and process external (environmental) and internal (network) information	Collect and process external (of antigen and tissue) and internal (of immune agents) information
Self-configuring organisation	Network-centric organisation
Promote in-network collaboration	Co-respondence

TABLE 4.3: Association points between the specknet and the CIS. Characterisation of information (i.e. internal or external) depends on the definition of the system boundaries.

already discussed in section 4.3.1, the architecture of the immune system includes networks at several layers, such as chemical, anatomical, vascular, which facilitate the gathering of individual immune cells to selective sites. The diverse cellular processors then mutually interact and influence each other performing, thus, immune processing.

4.3.4 Association Points between Specknet and CIS

The specknet and the CIS have several points of comparable nature, both structural and behavioural, see table 4.3. Both are complex systems with multiple autonomous units which collectively must produce coherent global behaviours. A rather broad, but of key importance, requirement for a specknet is to be able to maintain functioning as a network, while supporting an ongoing operation at the application level. The concept of maintenance is central to the CIS which besides regulating its own activities, it also offers health services to the body throughout the organism's lifetime. The functionality of a specknet relies largely on the efficient and effective handling and processing of information. This is partly captured from the environment and partly generated internally by specks. The CIS

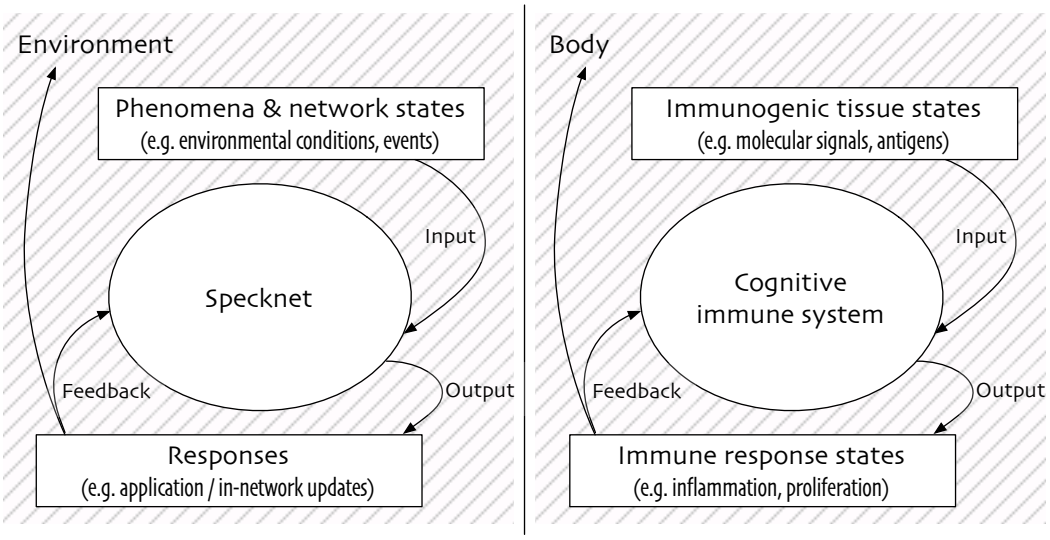


FIGURE 4.5: High-level computational analogy between the specknet and the cognitive immune system.

has developed mechanisms for processing antigenic information by integrating a vast range of chemical signals that are produced from the body's tissues as well as from immune cells themselves.

Another important requirement of a specknet is related to the organisational aspect of the system. Individual specks are brought together through communication links. These interactions need to be organised in ways that allow the system to be as little dependent on external coordination as possible, promoting collaboration among the system's constituent parts. Specks need to be enabled to perform self-configuring operations, keeping at the same time the overall cost of communication to a minimum. The core of the CIS architecture is supported by self-regulating immune networks. Anatomical networking mediates interactions among immune cells which, in turn, give rise to immune function by means of intense signalling without any external or globally centralised point of control.

Figure 4.5 illustrates a high-level computational analogy between the specknet and the CIS. The collection of immunogenic tissue states, which indicate the state of the body, are used by the immune system to determine appropriate response for retaining body maintenance. Similarly, the specknet receives input

related to environmental phenomena and in-network events, and issues responses associated with application or network matters accordingly.

4.4 Theoretical Focus

To place the CIS into context with the study framework for specknets of figure 3.6, the latter is contrasted with the strategy of the CIS from section 4.3.1. To remind, the cycle of operation for the specknet consists of the components: data collection, processing, decision-making and response. The strategy of the CIS for achieving maintenance is composed of the parts: recognition, cognition, and action. It is difficult to establish distinct mappings between the two schemes, due to the multiple scales and layers involved in either side. However, the general flow of operation is similar in both schemes, and in the case of the CIS points to the key process of co-respondence.

4.4.1 Co-respondence

The concept of co-respondence is described by Cohen as the central processing unit of the immune system [29]. Co-respondence is the process by which immune cells are led to joint immune decisions, ultimately forming the macroscopic immune response [27, p. 161]. It is supported by two main properties of immune cells. First, each immune cell sees and responds to different parts of the state of the body. Second, each immune cell interacts with other immune cells and collects as input part of their output.

Immune cells are divided into several classes. One such class is lymphocytes, which include T cells and B cells. Another class is monocytes, which include macrophages and dendritic cells [27, p. 106].[3] As illustrated in figure 4.6,

[3] After their introduction, Cohen uses the terms *monocyte* and *macrophage* interchangeably. For example, in [27, p. 108] he refers to dendritic cells as a type of macrophage.

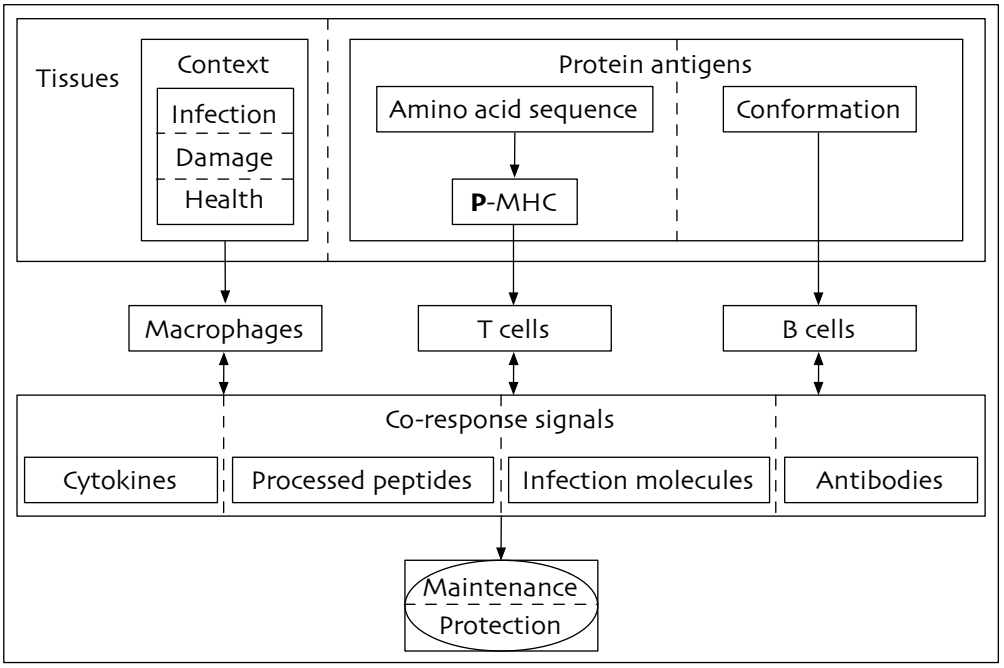


FIGURE 4.6: Co-respondence. Reproduced from [27].

macrophages, T cells and B cells play a central role in the process of co-respondence. The different perceptions that each of these immune cells provide are related to different aspects of the molecular environment of the body. Macrophages contribute contextual perceptions, that is they recognise the array of ancillary signals that are related to tissue damage, infection or health [27, p. 149]. Lymphocytes, on the other hand, contribute different antigenic perceptions, since they bear chemically distinct receptors. In particular, T cells recognise ligands which are composed of two pieces: a fragment of an antigen (peptide), attached to a host molecule (MHC) [27, p. 152]. B cells and the antibodies they secrete, recognise the conformations (shapes) of antigen molecules [27, p. 158].

When these semi-independent immune cells meet, they bring together their diverse perceptions, and through mutual interactions they integrate their individual states generating, thus, a collective response. The tissues of the body participate in this process too by continuously generating new signals as their state changes, influenced by the response of the immune system. It is from this mutual exchange of co-response signals that immune function achieves maintenance and protection

of the body. In this view of the immune system, no particular immune component is singled out to be presented as the controller of immune function. Rather, immune function is explained as the emerging result of the combined efforts of many diverse agents related to both the innate and adaptive arms of the immune system.

A figure of speech used by Cohen which indicates the intertwined relationships between the two aspects of the immune system, the innate/germ-line and the adaptive/somatic, describes T cells and B cells as the princes of adaptive immunity and innate macrophages as both kings and servants. T cells and B cells with their somatic receptors can recognise molecular structures that other cells are not able to see and can learn (adapt) from experience [27, p. 107]. Macrophages with their germ-line receptors are required for the efficient activation of T cells, but rely on antibodies produced by B cells in order to recognise a parasite and kill it [27, p. 108, 151].

4.4.2 Interpreting Cohen's Theory for Computation

The CIS relies on complex networking, "the raw material from which cognition emerges" according to Cohen [27, p. 166]. This makes the transition from the theoretical concept of co-respondence to a more tangible biological process, for use as source of inspiration computationally, a non-straightforward task. Unravelling the biological mechanisms that support co-respondence with the intention of capturing emergent properties of this key to cognition process is hard, due the immense biological complexity.

Consider, for example, the case of antigen recognition during a microbial infection. There are several pathways through which immune responses can develop depending on a large number of factors, such as the type of the infectious agent or the past experience of the organism's immune system. A microbe lands somehow

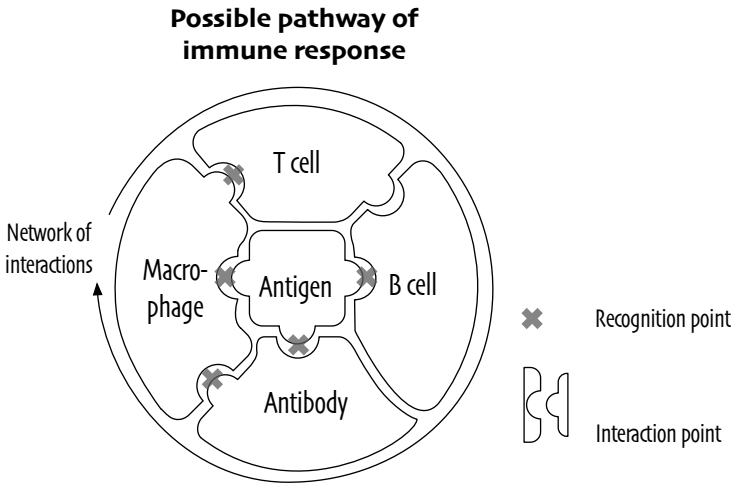


FIGURE 4.7: Possible pathway of immune response to a microbe; immune agents recognise directly or indirectly the presence of the antigen through a network of interactions.

in the body tissues and causes damage. Following one of the possible immune pathways, the recognition of the microbial antigen may roughly develop like so.

Resting macrophages sense the signals released by the dying tissue cells as well as some general structural characteristics of the microbe, which are common to broad classes of pathogens. This collection of input is enough to make the macrophage recognise the presence of the antigen and change its state to active [120, p. 43]. When the macrophage becomes fully activated, it expresses all the necessary input, which includes antigen fragments, that a naive T cell requires to become activated too. An active macrophage meets a naive T cell and, now, the antigen (or rather, some portion of it) is being recognised by the naive T cell. This recognition event changes the naive T cell to an experienced state and, also, forces it to assume a specific T-cell type [120, p. 7–9]. Naive B cells may also recognise the antigen in its native form, however this input is not enough to activate them. They require additional input which, in the case of T-cell dependent activation, is supplied by the experienced (helper) T cell [120, p. 28]. Activated B cells are also faced with a choice of type, and those that become plasma cells produce antibodies [120, p. 35]. Antibodies recognise and label antigens so that they be recognised and eaten by macrophages.

When examining the above series of events performed by the immune system while trying to deal with a microbe, at what point is it satisfactory to draw a line and claim that a successful antigen recognition has occurred? In the above loosely presented immune pathway, the antigen is directly or indirectly recognised by immune agents five times, see figure 4.7. Biologically, each recognition point has its own significance and all of them lead progressively to the desired response. Theoretically, Cohen's approach makes no suggestions as to which event of the recognition process is more important, because all of them are considered vital part of the picture that describes the immune function. How does one, then, interpret ideas found in the theory of the CIS?

The answer depends on the nature of the source idea. Part of the difficulty with trying to interpret co-respondence biologically, with the intention of further computational exploitation, is the fact that it is such a broad concept. For example, the concept of degeneracy explored by [9, 96], discussed in section 4.3.2, targets a very specific biological element, the antigen receptor. Co-respondence involves a multitude of immune agents interacting in varying temporal and spatial scales. Therefore, to regain focus, the study framework for specknets is revisited.

4.5 Biological Focus

Given that the first component in the study framework for specknets of figure 3.6 refers to collection of data, for the immune system this translates to biological process that pertain to the collection of input with regard to tissue states. One such process is antigen presentation.

4.5.1 Antigen Presentation

Lymphocytes contribute to the process of co-respondence various views of an antigen, see section 4.4.1. The process of antigen presentation is typically used

by immunologists to refer to the way T cells form their own antigenic view, namely how T cells recognise antigens. At this point, it is important to stress that according to Cohen recognition involves two conditions: *discrimination* and *response* [27, p. 125]. Discrimination refers to the detection of information, for example physical binding or sensing of chemical signals. Response refers to some form of ensuing reaction by which meaning is assigned to the detected information, see section 4.3.3. *Recognition*, thus, is defined by Cohen [27, p. 126] as:

> . . . the association of an *exclusive signal* with some type of *response*.

For instance, the T-cell recognition event being alluded to in section 4.4.2 involves the sensing by a naive T cell of input bore by an active macrophage (discrimination) and the subsequent positive activation of the naive T cell (response), which indicates that the sensed information describe an alarming situation, the presence of a microbe (meaning). In a different instance, a similar interaction between a T cell and a macrophage may lead to a negative reaction, such as inhibition or suppression of the T cell.

In this section, the examples of antigen presentation mentioned revolve around a positive T-cell activation, because they are derived from the example immune response of section 4.4.2. However, given Cohen's definition of recognition, it should be clear that positive activation is only *one* of the possible responses that may follow antigen presentation.

Antigen-presenting cells

T cells are able to recognise antigens only after these have been processed into peptides (fragments of protein) [27, p. 152–156]. Specifically, a T-cell receptor interacts with a compound ligand, namely a peptide connected to a MHC molecule. There are two types of MHC molecules: one is expressed on the surface of almost all body cells (MHC class I), while the other is produced only by certain types of

immune cells (MHC class II). The differences between the two MHC families are beyond the scope of this thesis. In short, the main idea is that MHC-I molecules are used to present peptides which are produced internally within the cell, for example from processing a self or viral protein. MHC-II molecules specialise in presenting peptides that come from proteins taken up from outside the cell or made by the cell. Those immune cells which are able to provide both classes I and II MHC molecules along with the necessary ancillary signals to activate T cells are called professional *antigen-presenting cells* and are briefly reviewed next.

Dendritic cells are considered the most potent of professional APCs [120, p. 42]. They are innate immune cells, that is, they express non-specific germ-line receptors. There exist several subsets of dendritic cells (DCs) throughout the body. Populations that reside in peripheral tissues have been characterised as powerful APCs due to their ability to stimulate naive T cells. In particular, DCs resting in tissues, sample the environment by taking in extracellular material and releasing it back out. Upon encountering microbial conditions, they undergo physical changes, such as increase of expression of peptide-MHC ligands and of other signals necessary for priming naive T cells. They also leave the tissues and migrate to nearby lymph nodes where naive T cells can be found.

Macrophages are another type of innate immune cell, which can perform various functions, such as garbage collection, killing or antigen presentation [120, p. 45]. They are different to DCs with respect to antigen presentation in that they lack mobility. That is, resting macrophages that become activated remain in the tissues. The role they fulfil there as APCs is to re-stimulate experienced T cells that have left the lymph node and travelled to the site of infection to provide help with the ongoing immune response.

B cells are the third type of professional APCs [120, p. 45]. Bearing specific somatic receptors, B cells are able to capture and process soluble antigen. Experienced B cells are thought to be used as APCs for helper T cells

after an immune response has progressed from the initial detection phase of infection by unknown pathogens, or during subsequent infections of the same pathogen. The high specificity of B cell receptors allows them to express peptide-MHC ligands a lot more efficiently and quickly for positive T-cell activation in comparison to the other APCs.

4.5.2 Selection of an APC

Of the three professional APCs, the type selected for closer examination is the dendritic cell. The main reason for this choice is the *migratory* element of the DC behaviour which offers, always with regard to specknets, an additional, interesting dimension for exploration. Moreover, although any of the APCs essentially performs some form of data collection for the immune system, the function of dendritic cells seems to be primarily involved in the *early* stages of a potential immune response. At least in the case of the example presented in section 4.4.2, the other two APCs appear to enter the network of co-respondence at a later time. Hence, their functionality partly relies on an intricate chain of previous immune events, unnecessarily complex to attempt to unfold for the purposes of this investigation.

4.5.3 The Dendritic Cell within AISs

Recent research in the area of anomaly detection for computer security exploit the functionality of DCs, owing to Matzinger's danger model [87]. Twycross [130] explores how innate immunity can be incorporated into the design of AISs, so that these may then be applied to real-world problems. A number of design principles based on the innate immune system are proposed, and a software framework is presented, called libtissue, in aid of implementing and testing AIS algorithms that are based on both innate and adaptive immune mechanisms. In addition, an AIS algorithm is presented, called TLR, designed to perform process anomaly

detection. The TLR algorithm models the interactions between DCs and T cells as described by a certain immunological model of DC polarisation of helper T cells. Further details about the algorithm are beyond the scope of this review. Nonetheless, it is noteworthy to mention an important decision made on the design level of the algorithm, which is also supported by the libtissue framework, that of compartmentalisation of the environment within which cell interactions occur. Virtual compartments are used to represent the different locations within the body where different immune cell functions take place, a characteristic that is usually ignored in AISs.

Greensmith et al. [54, 55, 56] develop a population-based anomaly detection algorithm, named the dendritic cell algorithm (DCA), based on a signal processing model abstracted from collaboration with experimental immunologists. Two main stages of the DC functionality are considered, the sampling of tissues and the presentation of collected antigen and corresponding signals to T cells in the lymph node, with the main focus placed on the first stage. The resultant algorithm incorporates a fusion technique of multiple types of input signals to determine the output signals (context) used for assessing whether the process IDs (antigen) encountered during computer system operation are anomalous.

An interesting observation about the abstracted model that underlies the DCA is that the antigen is not inherently assumed to be dangerous. Rather, the decision about whether an antigen is anomalous depends on the signal context that accompanies the antigen during presentation [54, p. 85–86]. The signals alone may provide indications about the state of the tissues, but specific information about a potential problem is represented by the antigen itself. This interpretation is, remarkably, in line with Cohen's informational view of the immune function, see section 4.3.3, only in [54] it is obtained from studying Matzinger's danger model.[4]

[4]In [12], the paper in which Cohen discusses the immune system in informational terms, he also explains his views on Matzinger's concept of 'danger.' In short, Cohen argues that, even if the idea of 'danger' is accepted, it would still be an incomplete view of the immune system, because it could explain only the first step of immune function. Different types of

4.5.4 Novelty of Proposed Approach

The work in this thesis differs from the AIS works of the previous section in the following ways. Firstly, the research in this thesis is not problem-oriented, in that it does not examine or target a specific application problem, such as anomaly detection. Rather, it explores the potential of specknets for use in investigating the complex character of the immune system from a computational and engineering perspective.

Another difference is the theoretical context within which the functionality of DCs is interpreted. The reviewed works rely heavily on ideas coming from Matzinger's danger model, where great emphasis is placed on the innate aspect of the immune system. In particular, the detecting ability of DCs is thought to play a determining role in immune function. In contrast, this work relies on Cohen's cognitive view, where DCs are seen as part of the network of actors that contribute to immune function, by gathering and transferring information.

Finally, in terms of DC functionality, the key aspects examined are different in all three bodies of work. Twycross [130] is mainly concerned with the interactions of DCs with T cells. Greensmith [54] primarily studies the sampling of tissues, whereas the focus of this thesis is on the migrating behaviour of DCs.

4.6 Conclusion

This chapter has presented the methodology followed in this thesis. It, then, continued with exploring the first four steps, the outcome of which was to identify the DC as appropriate for further exploration, viewed within the theoretical context provided by the CIS. In the following chapter, the functionality and behaviour of the DC are explored in detail.

'danger' exist, each needing a different response. After 'danger' has been detected, how does the immune system decide what type of response to mount?

Chapter 5

Dendritic Cells: Life Cycle and a Simulation Model

5.1 Introduction

This chapter focusses on the dendritic cell. The aim is to understand the immunological role of DCs. Section 5.1.1 presents the contextual dimensions within which the investigation proceeds. These are used to help guide exploration of the relevant immunological literature on DCs, which is presented in section 5.2. Section 5.3 examines closer certain aspects of the life cycle of a DC through the development of a simulation model. Finally, section 5.4 discusses research practice within AISs with regard to immunobiological surveying, through an example case of DC use identified in the literature review of chapter 2.

5.1.1 Research Dimensions

The behaviour of leukocytes is influenced by a variety of factors, which can be summarised under a number of dimensions such as *anatomy*, *cell physiology* and *body state*. When studying the immunological literature, it is important to take

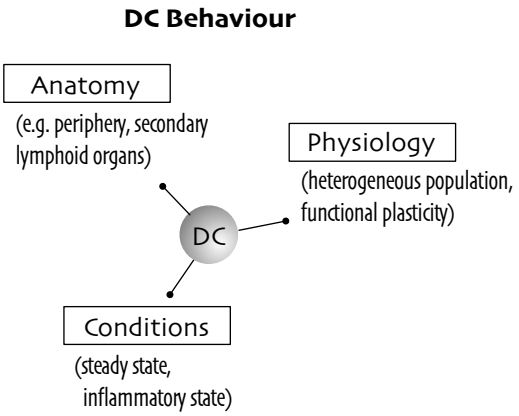


FIGURE 5.1: Dimensions for consideration when examining immune elements for immune inspiration.

such dimensions into consideration for two reasons. Firstly, they help obtain a fuller picture about the workings of specific immune elements and, secondly, they help reduce the risk of forming erroneous assumptions about these elements.

Figure 5.1 shows a set of factors that influence the behaviour of DCs within each of the above dimensions, as they become evident from researching the immunological literature in section 5.2. In brief, DCs develop into a diverse set of subpopulations shaped by body's anatomical arrangements, and conditions of local microenvironment and nearby linked areas. Trafficking of DCs is largely influenced by the phenotype into which they develop. Some DC subtypes exhibit potential for further functional plasticity throughout their life cycle which additionally is dependent on present conditions of tissue state. These points are expanded in the following section, and also inform the discussion in section 5.4.

5.2 Dendritic Cells in Immunological Research

Before starting with this section, it is important to make clear that the author has no biological background, so whatever is presented next is based purely on the author's understanding of studying the material collected from the immunological research literature. Although every effort has been put in to explaining

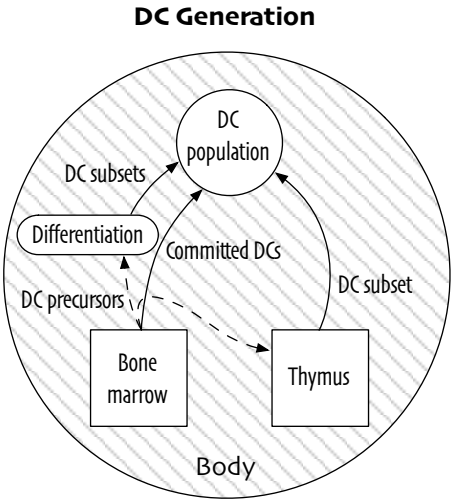


FIGURE 5.2: Primary lymphoid tissue provide the body with dendritic cells.

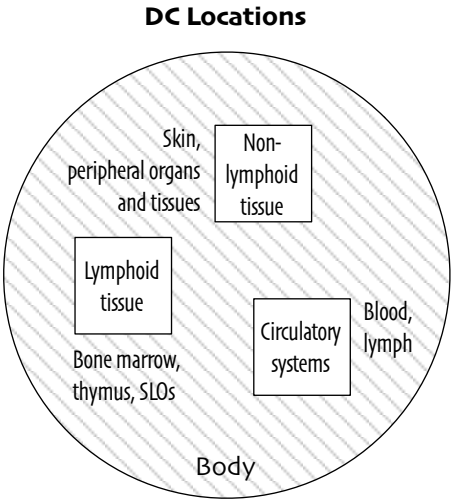


FIGURE 5.3: Body locations wherein dendritic cells can be found.

the subject as clearly and accurately as possible, this review may still suffer from misunderstanding issues. Moreover, distinguishing between murine and human models is deliberately avoided, as well as referring to any kind of biological markers throughout the review, due to the author's limited knowledge on the subject. As such, the reader is strongly encouraged to refer to the original publications for further biological details.

5.2.1 Development and Distribution

The population of DCs is heterogeneous, that is they are not a single cell type [6, 74, 117, 144]. The bone marrow is the ultimate origin of all DCs, however only a portion of the DC population comes from cells that exhibit a phenotype with clear DC characteristics upon leaving the source. The rest of the population is derived from precursor cells which differentiate into distinct DC subsets corresponding to the various tissue types found throughout the body. In addition, a number of DCs are generated from precursors within the thymus which, along with the bone marrow, constitute the primary lymphoid tissue (PLT). Figure 5.2 illustrates the body sources that supply with new cells the population of DCs within the body.

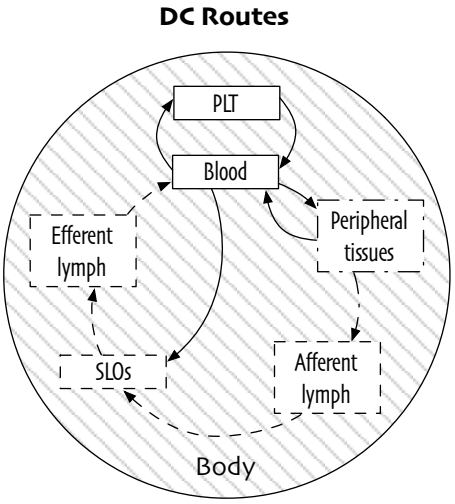


FIGURE 5.4: Migratory routes of dendritic cells and their precursors. Adapted from [6].

A generic model used by immunologists to describe the development of immune cells identifies two separate developmental pathways: the *lymphoid* and the *myeloid*. This means that some immune cells have been identified to restrictively come from common lymphoid precursors, such as B and T cells, while other immune cells have been characterised to develop from a different lineage originating from common myeloid precursors, such as monocytes and macrophages. Evidence show that DC subsets can be generated along both pathways, that is, from common lymphoid or myeloid precursors.

Anatomically, DCs can be found in several locations including lymphoid tissue residing within the PLTs and secondary lymphoid organs (SLOs), such as lymph nodes and spleen (figure 2.3), and non-lymphoid tissue such as the skin and other peripheral tissue. No correlation exists between the DC developmental pathway and the type of tissue in which the cells may be found; for instance, lymphoid tissue can contain DCs of both lymphoid and myeloid origin. After their generation from the bone marrow, precursors and committed DCs migrate to tissues and organs via the blood. This is the first of a number of migration events some DC subtypes can undergo, and the only migration event for those DCs that assume fixed positions within their destination organs. Blood contains

a mixture of precursor and experienced DCs following various trafficking routes with several potential destinations, which depend on the type of cell and state of the local microenvironment. For example, certain DC precursors recirculate continuously between the blood, peripheral organs and lymphatics and can give rise to DCs where and when suitable differentiation conditions exist.

A summary of the various locations within the body where DCs can be found is shown in figure 5.3. Additionally, figure 5.4 outlines the trafficking routes travelled by DCs and their precursor cells. Originating in the PLTs, precursor and committed DCs enter blood circulation. From there, they have the options of direct access to peripheral tissues or SLOs, along with re-entry into the bone marrow. Cells that enter peripheral tissues can leave again by either returning to the blood or entering lymphatics. *Afferent lymphatic vessels* lead exiting cells to draining lymph nodes and other SLOs. To leave the latter, cells go through the *efferent lymphatic vessels* which drain back into blood circulation. For more details on DC subsets and their migratory patterns refer to [6].

5.2.2 Immature vs. Mature Model

In standard immunological literature, the DC is known to play a crucial role during the early stages of antigen-specific immune responses. Its function is explained by means of the immature-versus-mature model, which has been used as basis for the general study of DC biology by immunologists in previous years [117]. In brief, this standard model focusses on DCs sited in peripheral tissues and refers to them as being in an *immature* state. These immature DCs are mainly characterised by the following attributes. Firstly, their enhanced capability of capturing antigen, irrespectively of the surrounding tissue state, that is whether they are under steady-state or pro-inflammatory body conditions. Secondly, their low motility, limited to the local tissue microenvironment. Thirdly, their physical inability to cause T-cell stimulation, if they were to come across a T cell in peripheral tissues.

The immature state of tissue-resident DCs is considered unstable, because given the appropriate accompanying signals antigen uptake may cause immature DCs to undergo further developmental stages leading to a *mature* state. Mature DCs exhibit characteristics such as: rapid decline in their antigen-uptake ability; significant changes in their shape, for instance increase in the density of peptide-MHC ligands on their surface; enhanced motility and selective movement through the lymphatics to SLOs; and, expression of special cytokine profiles important in the education of naive T cells during antigen presentation in lymphoid tissues.

Immunologists develop a wide range of assays using various techniques to obtain and evaluate experimental data about their subject of study—an indicative list of such assays, used to study the specific topic of DC migration, can be found in [109]. Advancements made in the technology available for conducting wet-lab experiments allow new techniques to be developed, which bring to light new evidence that contradict existing immunological models or indicate false assumptions have been made in the past about certain topics. The aforementioned model of DC function is no exception, and in sections 5.2.3 and 5.2.4 a review is given of how the perception about the role of DCs has evolved within the immunological research literature over the past decade. It should be noted that this is far from an exhaustive review of immunological publications relating DCs, yet it is intended to provide helpful insight into the subject.

5.2.3 Immunogenic vs. Tolerogenic Effects

Dendritic cells are established professional APCs, presenting processed antigen to T cells under a variety of settings. Interactions between DCs and T cells can lead to: positive T-cell stimulation, referred to as *immunogenic* response; regulatory effector functions, typically called *tolerogenic* responses; or no effect at all.

One way of interpreting the functional division of DC-associated immunogenic versus tolerogenic effects is to consider the developmental pathways of DCs [117].

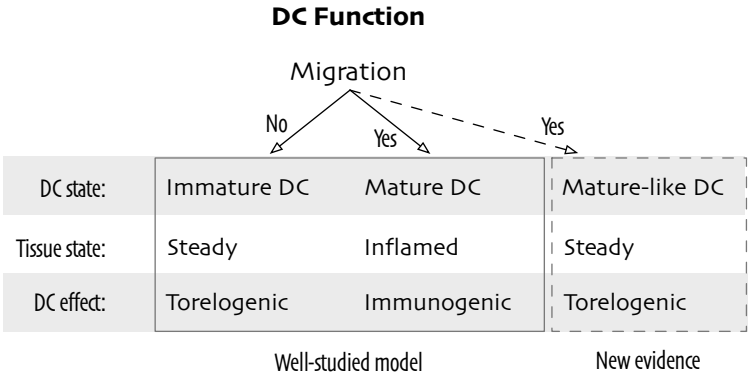


FIGURE 5.5: A summary of early and recent observations about the function of myeloid DCs which led immunologists to re-evaluate the well-known immature versus mature functional model of DCs.

In this context, it is thought that lymphoid DCs are primarily undertaking a regulatory role within immunity. For example, thymic DCs, a lymphoid-related DC subset sited within the thymus, is known to promote negative selection of thymocytes, precursors of T cells. On the other hand, myeloid DCs are considered responsible for mainly mediating stimulatory responses. A typical example of such myeloid DCs are immature DCs that are stimulated in the periphery and, subsequently, turn into T-cell activating, mature DCs at lymph nodes, triggering an antigen-specific immune response. Due to the importance of displaying an active role in immunogenicity, peripheral tissue-resident DCs became the subject of intensive study, with Langerhans cells, a type of DC found within the epidermis, serving as the prototype immature DC.

Studies focussing on myeloid-related DCs placed the functional division of tolerogenic and immunogenic role between the immature and mature differentiation stages of these cells [86, 108], see section 5.2.2. That is, the immature phenotype of DCs was associated with the induction of T-cell anergy in the steady state, whereas the mature phenotype of DCs was linked with the presence of inflamed tissue and, thus, became a sign of positive T-cell activation. However, observations of DC migratory activity under *healthy* conditions caused immunologists to reexamine the existing model of DC function, see figure 5.5. As a result, some

immunologists revised the well-known immature versus mature model, and proposed the term 'semi-mature' to describe DCs exhibiting a tolerogenic migratory phenotype, and the previously 'mature' DCs were re-introduced as 'fully mature' DCs [86]. Others posed the question of whether DC migration needs to be decoupled from maturation and treated as a separate function altogether [108].

5.2.4 Migration

The migration of DC subsets and their precursors is a largely unexplored area within immunology, but gains increasing interest due to its potential for therapeutic manipulation in clinical application. Recent immunological publications that review existing knowledge relating to the trafficking behaviour of DCs, emphasise the numerous gaps and questions that exist around this topic [6, 109, 110]. In particular, there are open questions with respect to the environmental signals that prompt DC precursors to change into a subset-specific phenotype. Similarly, the specific events that underlie migration of DC subsets from periphery to lymphoid tissue in the steady state remain elusive. Although lymph-migration of DCs from inflamed tissue is better studied, it is unknown, for example, whether all or just a fraction of DCs entering afferent lymphatics arrive in the lymph node, or whether mature DCs that make it to a lymph node can mobilise back to the blood, either directly or through the efferent lymphatics, disseminating, thus, processed antigen at distal sites. Moreover, it is not entirely clear which DC subsets reach lymph nodes through which route, via blood or lymph, and what the significance of these different points of entry might be.

An interesting detail highlighted in [110] concerning Langerhans cells, the prototypical DC subtype, is that recent findings about their life cycle are incompatible with the paradigm developed in the past. For example, while it was previously thought that Langerhans cells are essential for initiating T-cell priming in the lymph node, evidence now shows that in certain cases they reach lymph nodes

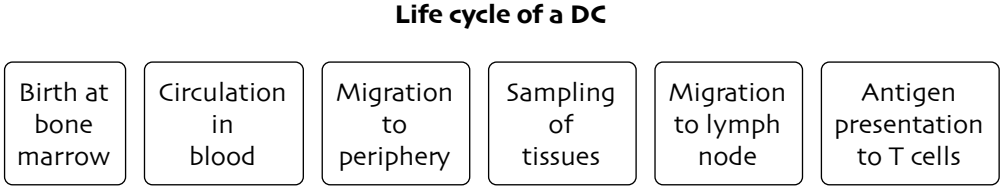


FIGURE 5.6: Basic model composed of a series of phases captured from the life cycle of an immune cell that develops into a peripheral tissue-resident DC.

slower than expected, when an immune response is already under way; such behaviour, is speculated, could indicate that Langerhans cells assume at least in some cases a role of immunoregulation, which is the inverse of their popular immunogenic function.

Another interesting note indicated in the same article [110] refers to plasmacytoid dendritic cells (pDCs). This DC subtype enters peripheral organs in low levels in the steady state, but increases in numbers in inflamed tissues. However, its migratory behaviour seems to greatly differ from the conventional model, since pDCs appear to enter lymph nodes exclusively through the blood route. It is, therefore, theorised that pDCs may support the antigen-presentation function of myeloid DCs rather than presenting themselves, or they may provide a backup system by arriving to lymph nodes through an alternative route.

5.2.5 Life Cycle of a Dendritic Cell

To conclude this review, a basic model of DC life cycle is outlined, shown in figure 5.6, upon which the framework for the experimental work that follows in chapter 6 is based. The model revolves around a simplified version of the life cycle of an individual DC. Specifically, the model captures a series of distinct stages in the life of an immune cell that develops into a peripheral tissue-resident DC, starting with its birth at the bone marrow. Following that, the cell migrates first into the blood circulatory system and, then, commits to the subtype of a tissue-resident DC by moving to the periphery. There, the DC samples the surrounding

tissue until it either reaches the end of its life span or migrates to a nearby lymph node. In the latter case, the DC comes into contact with naive T cells and engages with them in the process of antigen presentation.

5.3 A Model of Immunogenic Dendritic Cells

Having investigated DCs within the context of the immunological research literature, in this section the focus narrows on specific aspects of the functionality of DCs. These are examined within the context of a modelling exercise. In particular, the three final stages of the basic model of figure 5.6 are examined and inform the development of a simple agent-based model (ABM). Section 5.3.1 discusses the aim and scope of the modelling approach. The underlying immunology upon which the model is based is expanded on in section 5.3.2. Section 5.3.3 presents the ABM in detail. Section 5.3.4 explains the desired behaviour that the ABM is expected to simulate and provides results to validate the model against the specified desired behaviour.

5.3.1 Aim and Scope

The aim of this modelling exercise is to produce a model that serves as a basis upon which to further investigate the relationship between the immune system and the specknet. For this purpose, a high-level model of the immunological processes in focus is deemed sufficient as the first step into exploring the two systems in more practical terms. As such, no attempt is made to develop a model that mimics the underlying biological events linked to the selected processes, which precludes any possible feedback to biology.

The immunological processes considered are related to the functionality of tissue-resident DCs and involve: sampling of tissues; migration from tissue to lymph node; and activation of T cells at the lymph node. These phases are treated as a

chain of events that lead to an immune response, similar to the pathway discussed in section 4.4.2. In the example response of figure 4.7, the point of interaction involving macrophages and naive T cells leads to the activation of helper T cells. In the case of this modelling exercise, a separate pathway is assumed that leads to the activation of a different type of T cell, known as cytotoxic T cell. Once activated, cytotoxic T cells travel to the site of infection where they attack infected cells [120, p. 62]. To summarise, the immune functionality considered for the modelling exercise relates to the special case of antigen presentation by tissue-resident DCs to naive T cells in the case of microbial infection leading to the priming of cytotoxic T cells.

It should be noted that the interest of the investigation lies in the overall scenario of eliciting a response, with the attention drawn primarily to the role of DCs as migratory collectors of data. In other words, the investigation mainly concentrates on the ability of DCs to function as scouts and reporters, and is less concerned with the actual information (antigen and context) collected and processed by DCs, or the type of response that develops from the interaction between DCs and T cells.

Another point worth clarifying is that, although immune molecules are as important to immune function as immune cells, they are not examined in detail. Their overwhelming complexity is considered superfluous for the objective of this modelling exercise. Therefore, any chemical signals involved in the relevant underlying biological events are modelled by single collective proxies, rather than individually.

5.3.2 Immunological Basis

The immunological basis of the ABM is drawn from textbooks of the current immunological literature [72, 120]. Due to the generic level at which the underlying biological processes are treated during abstraction, the resulting model contains

Immune elements	**In the model**
Anatomical Features	
Spatial organisation:	Peripheral tissue and lymph nodes are represented, but lymphatics are replaced by gradients
Lymph-node positioning:	Corresponding agents are given random positions
Lymph-node internal organisation:	Is not considered
Overall Functionality	
Molecular signalling:	Reduced to two kinds of spatial signal, to indicate presence of different sites
Type of stimulating agent:	Assumed to be infectious; is not further subclassed
Type of response:	Hard-wired to a single kind of effector activity
Functionality of Dendritic Cells	
Type of dendritic cell:	Tissue-resident DC, behaviour considered is related to immature and mature states
Conditions of migration:	Migration occurs only after exposure to infectious signals

TABLE 5.1: A list of assumptions and simplifications made in the model with respect to different aspects of the underlying immune elements.

gross assumptions and simplifications with respect to all involved aspects, from anatomical features of the natural immune system to functionality aspects of the selected immune agents. The underlying immune elements are summarised below alongside the assumptions and simplifications made in the model; an outline is listed in table 5.1.

Anatomical Features

In the natural system, the underlying biological events take place in various areas of the body, see figure 2.3. DCs perform sampling at the peripheral tissues.

Activated DCs interact with naive T cells inside SLOs, such as lymph nodes. Trafficking of the immune cells between different areas of the body, for instance the migration of DCs from the periphery to a lymph node, is supported by the lymphatic vessels.

Furthermore, with regard to positioning, certain areas of bodily tissue are more likely to become infected, at least initially, than others [120, p. 73]. For example, tissues close to the skin may become a point of entry for pathogens via a wound, or intestinal tissue may become infected because of consumption of contaminated food. As such, sets of SLOs are positioned in strategic locations nearby possible routes of pathogenic entry into the body.

Given the adopted modelling approach, representation of the above anatomical features, that is the peripheral tissue, the lymph node and the lymphatics, is done at a level of minimal detail. For example, in the ABM lymph nodes are considered as distinct agents but without their internal anatomical organisation [72, p. 8]. In addition, modelling of the lymphatics relies exclusively on gradients formed by the diffusion of special signals, instead of using a dedicated agent to form a virtual network of pathways. In terms of arrangement, the anatomical agents are assigned random locations, disregarding any seeming indications of arrangement observed in the bodily tissue.

Overall Functionality

Molecular signalling is integral to the underlying immunological processes. When infection occurs, cytokines are released by various cells in response to the situation, leading to the development of inflammatory conditions at the site of infection [72, p.45]. DCs situated nearby a site of infection release chemoattractant cytokines (chemokines) which mediate, along with other inflammatory agents, the recruitment of leukocytes to the area of incident [72, p.77]. For instance,

chemokines contribute to the guidance of effector T cells during their migration to the site of infection, after activation at a lymph node [72, p.425].

In the ABM, molecular signalling informs guidance of mobile agents using the notion of chemotaxis [72, p. 79].[1] In particular, two types of signals are used. One signal is used as a proxy for those cytokines enabling the migration of DCs to lymph nodes. Another signal denotes the presence of infected sites in the model to represent inflammatory cytokines that attract effector T cells towards sites of infection in the body.

With respect to infection and subsequent responses, in the natural system disease is caused by a variety of microorganisms damaging tissues in different ways [72, p. 412]. The different pathogens are cleared with the help of various effector mechanisms [72, p. 429]. Since no specific infectious conditions are targeted, the ABM contains agents assumed to be infectious with their impact measured at an arbitrarily quantifiable level. The effector response to the discovery of such infectious agent is the generation of mobile agents based on the behaviour of cytotoxic T cells. These cells become activated in the lymph nodes via interaction with mature dendritic cells and travel to kill the infected cells [72, p. 342–343].

Functionality of Dendritic Cells

In terms of DCs functionality, the behaviour in focus is that of tissue-resident DCs within the immature versus mature model, examined in sections 5.2.2 and 5.2.3. In particular, the ABM includes a minimal representation of a DC that samples from the tissue environment only infectious signals. As such, in the model migration follows maturation, that is a DC agent switches from a scouting to a reporting behaviour only after it has been exposed to infectious signals.

[1] Chemotaxis is a well-known design pattern in biologically inspired computing [13], used for path creation. Gradients of signals provide routes based on maximum concentration toward sites of interest.

5.3.3 The Agent-Based Model

The implemented ABM can be summarised as follows: a constant number of scouting dendritic cells move at random, sampling the tissue for infections. Whenever a dendritic cell crosses an infected site, it accumulates infectious signals until an arbitrary threshold is reached. When this happens, the scouting dendritic cell changes into a reporting dendritic cell which moves towards a lymph node. Upon arrival at a lymph node, the reporting dendritic cell causes a number of effector T cells to be released. These move towards infected sites, where they reduce the infectious signals. The goal of the overall process is to eliminate infected sites. The deliberate movement of reporting dendritic cells to lymph nodes and effector T cells to infected sites is facilitated by gradients. Figures 5.7 and 5.8 show diagrams outlining the behaviour of the two cell agents, the scouting DC and effector T cell respectively.

The modelling tool adopted is NetLogo [138], a popular generic programmable modelling environment for building multi-agent models. The code of the model is listed in appendix B. A snapshot of the model running is shown in figure 5.9.

Detailed Description

The model contains high-level representations of the bodily environment and three main immune elements: lymph nodes; immune cells; and, chemical signals. Six types of agents and three types of signals are included. Each is described in turn below. All model parameters are summarised in table 5.2.

Stationary Agents

Tissue environment: It is represented using the topology of a torus with dimensions: `min-pxcor` × `max-pycor`. In other words, the tissue environment

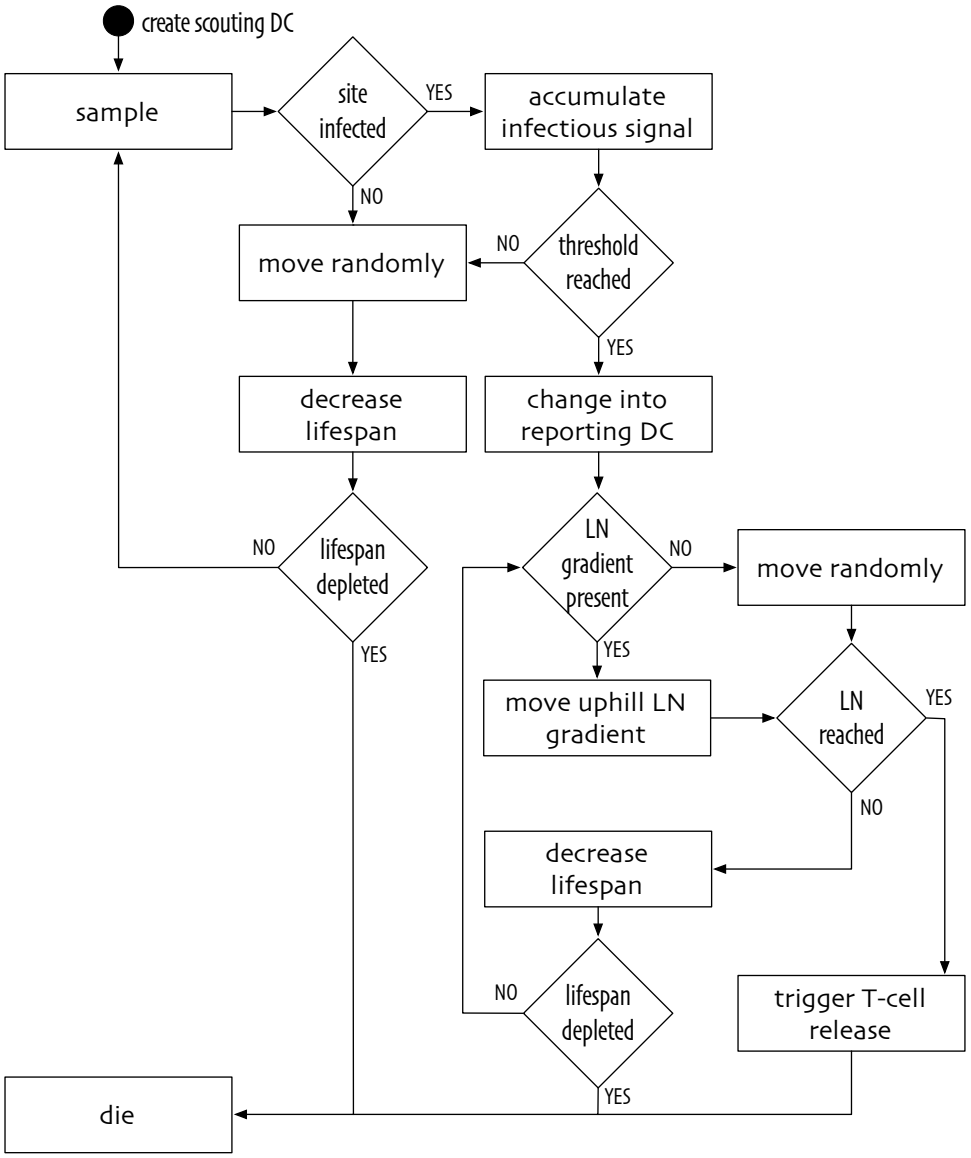


FIGURE 5.7: Flow diagram of the scouting DC behaviour.

consists of a grid of patches[2] which exist on a surface with edges connected to each other, allowing the model world to wrap around.

Lymph-node locations: At the beginning of a run, a total of `lymph-node-count` lymph-node locations are generated at random patches within the tissue environment. Each lymph-node location builds up a gradient around itself by releasing a signal of type *lymph-chemical*.

[2]In NetLogo, a patch is the term for a stationary agent.

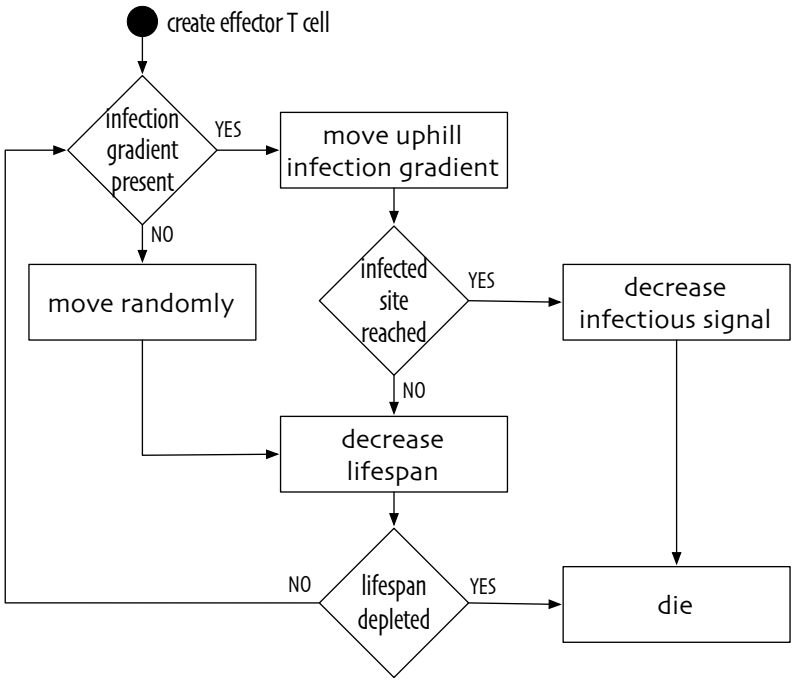


FIGURE 5.8: Flow diagram of the effector T-cell behaviour.

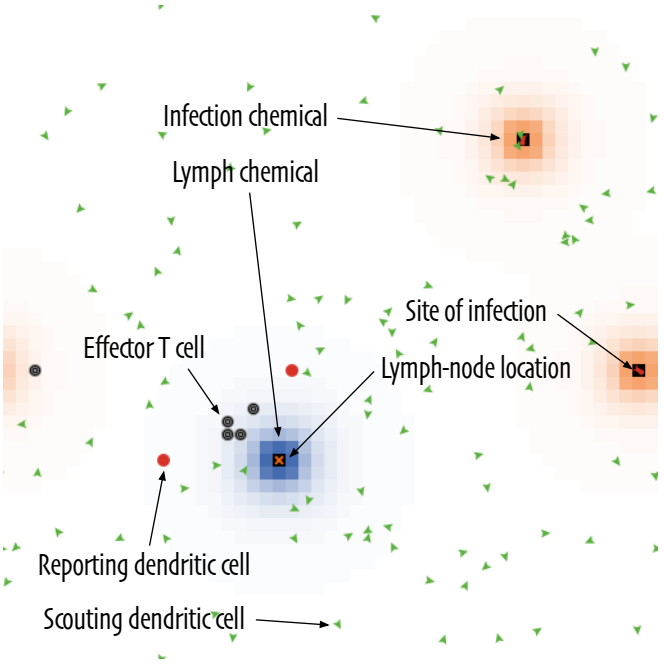


FIGURE 5.9: A snapshot of the agent-based model running.

Model parameters	
Stationary agents	
Tissue environment:	`min-pxcor`; `max-pycor`
Lymph-node locations:	`lymph-node-count`
Sites of infection:	`infection-count`
Mobile agents	
Scouting dendritic cells:	`d-cell-count`; `mean-d-cell-lifespan`; `std-d-cell-lifespan`; `reporting-threshold`
Reporting dendritic cells:	-
Effector T cells:	`t-cell-release-rate`; `mean-t-cell-lifespan`; `std-t-cell-lifespan`;
Signals	
Lymph-chemical:	`lymph-release-rate`; `lymph-diffusion-rate` `lymph-decay-rate`
Infection-chemical:	`infection-release-rate`; `infection-diffusion-rate`; `infection-decay-rate`
Infectious signals:	`infectious-level`

TABLE 5.2: List of model parameters.

Sites of infection: In manner similar to lymph-node locations, a number of infections `infection-count` is set from the beginning, each building up a gradient by releasing a signal of type *infection-chemical*. In addition, each site of infection is the source of *infectious signals*.

Mobile Agents

Scouting dendritic cells: At the beginning of a run, a population of size `d-cell-count` is created on random patches. Each scouting DC has a lifespan value drawn from a gaussian distribution N(`mean-d-cell-lifespan`,

`std-d-cell-lifespan`), and upon death it is replaced by a new one. Scouting DCs move at random through the tissue environment, sampling for and accumulating infectious signals. With every movement their lifespan decreases by one unit.

Reporting dendritic cells: Scouting DCs change into reporting DCs, which retain the original remaining lifespan, if the amount of infectious signals collected from sites of infection exceeds a fixed threshold value `reporting-threshold`. Reporting DCs move towards a lymph-node location following existing lymph-chemical gradients. In the absence of a gradient, they move at random. Upon reaching at a lymph-node location, reporting DCs die and are replaced by new scouting DCs.

Effector T cells: They are released from a lymph-node location upon arrival of reporting DCs. Every reporting DC invokes the release of effector T cells at a rate `t-cell-release-rate`. Effector T cells are attracted towards sites of infection via their surrounding gradients. In the absence of such gradient, they move randomly. Effector T cells have a limited lifespan of value drawn from a gaussian distribution N(`mean-t-cell-lifespan`, `std-t-cell-lifespan`) which decreases with each step taken. Those dying off are not automatically replaced; new ones are only generated by reporting DCs reaching a lymph-node location. Each effector T cell that makes it to a site of infection reduces the level of infection at that site by a single unit and then dies.

Signals

Lymph-chemical: An amount of this signal is released from each lymph-node location with each iteration at rate `lymph-release-rate`. Diffusion starting from the patch of a lymph-node location causes each patch of the tissue environment to share `lymph-diffusion-rate` percent of the value of its

lymph-chemical signal equally between its eight neighbouring patches. Signal levels on each patch decay by `lymph-decay-rate` with each iteration.

Infection-chemical: In a similar manner to lymph-node locations, sites of infection release this type of signal at rate `infection-release-rate` per iteration. With each iteration, the infection chemical on each patch diffuses equally among the eight adjacent patches at a rate `infection-diffusion-rate`, starting from the patch at the site of infection, and decays by `infection-decay-rate`.

Infectious signals: They characterise sites of infection and are initialised to value `infectious-level`. Scouting DCs accumulate infectious signals they came across while sampling the tissue environment. The level of infectious signal at a site of infection is reduced by one unit every time an effector T cell arrives at such a patch.

5.3.4 Validation

The ABM is validated against high-level immune functionality. The model is not validated against any immunological data, qualitative nor quantitative, since the intention is not to produce a biological simulation, see section 5.3.1. Rather, the validation is done against whether a number of behaviour-related properties of the underlying immunological processes are captured. These properties are:

- Dendritic cells as scouts: tissue-resident DCs sample input from tissues.
- Dendritic cells as reporters: activated DCs travel to lymph nodes to present information collected from peripheral tissues.
- System response: cytotoxic T cells leave lymph nodes to participate in reactions which ultimately eliminate infection at affected sites in the periphery.

Property	Description	Measure
Dendritic cells as scouts	Tissue environment is adequately sampled	Coverage
Dendritic cells as reporters	Reporting DCs reach lymph-node locations	Population of effector T cells
System response	Infections are cleared	Infection level

TABLE 5.3: Measures for model validation, derived from listed properties.

Quantitative measures are derived from the above properties, listed in table 5.3. These measures indicate the extent to which each property is observed in the model, either directly or through a proxy measurement. For example, the scouting behaviour of DC agents is examined by measuring directly the number of visits environment patches accept from scouting DCs, whereas the reporting behaviour of DC agents is tested by monitoring the number of effector T cells in the system, since T-cell agents are only produced in response to reporting DCs reaching a lymph-node location. The system's response is indicated by the level of infection.

It should be noted that, given the simplified model, it is impractical to try and select input parameters from the immunological literature. Moreover, since the model is only used in qualitative sense to investigate high-level functionality, there is no need to perform a wide-ranging exploration of parameters—there is no intention to optimise the model. As such, below are presented example results that are indicative of the system's behaviour with respect to each of the properties listed in table 5.3.

Dendritic Cells as Scouts

The function of scouting DCs to adequately sample the tissue environment is evaluated through the coverage they achieve when moving around the patches of tissue environment, including sites of infection. The coverage is measured by calculating the percentage of patches that have been visited by scouting DCs at

Description	*Value*
`min-pxcor`	-50
`max-pycor`	50
`mean-d-cell-lifespan`	50
`std-d-cell-lifespan`	10

TABLE 5.4: Input parameters for coverage.

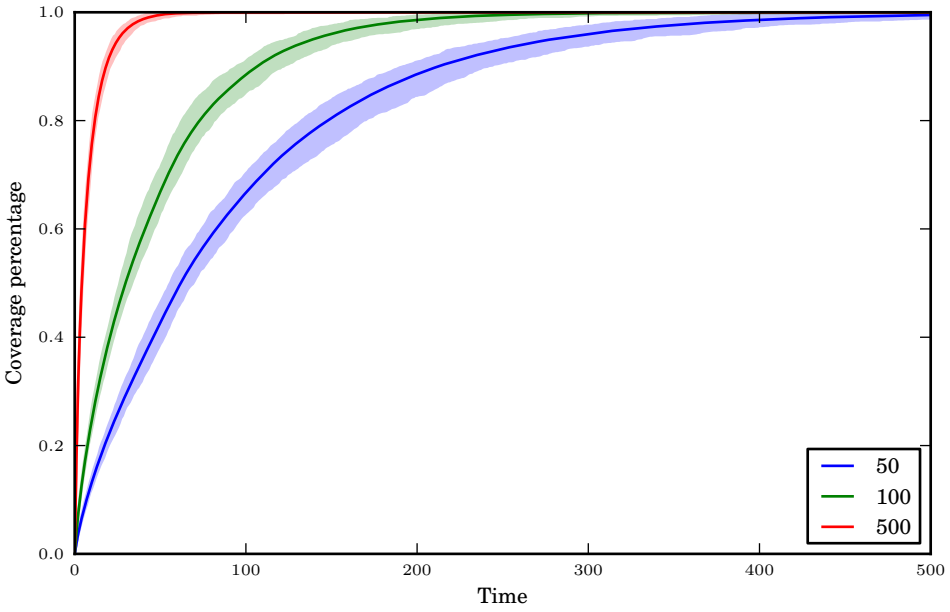


FIGURE 5.10: Coverage results confirm scouting function.

least once. The average life span of scouting DCs is 50 with a standard deviation of 10, and the size of the world in which they move is a 51×51 torus, see table 5.4.

Figure 5.10 shows results for population sizes of 50, 100 and 500 scouting DCs. Plotted are the mean from two hundred iterations with errors at the minimum and maximum values. The figure indicates that, given enough time, scouting DCs are able to sample the entire tissue environment. As expected, the greater the population size the faster the coverage converges to one.

Description	*Value*
`min-pxcor`	-100
`max-pycor`	100
`lymph-node-count`	20
`infection-count`	100
`lymph-release-rate`	15
`lymph-diffusion-rate`	1.00
`lymph-decay-rate`	0.10
`infection-release-rate`	10
`infection-diffusion-rate`	1.00
`infection-decay-rate`	0.10
`d-cell-count`	500
`mean-d-cell-lifespan`	50
`std-d-cell-lifespan`	10
`t-cell-release-rate`	2
`mean-t-cell-lifespan`	25
`std-t-cell-lifespan`	10
`reporting-threshold`	5
`infectious-level`	15

TABLE 5.5: List of input parameter to the ABM.

Dendritic Cells as Reporters

The function of reporting DCs to deliver collected information to lymph-node locations is measured by a proxy which monitors the number of effector T cells released, as this event occurs only when a reporting DC reaches a lymph-node location. Figure 5.11 shows results from an example run, the input parameters of which are listed in table 5.5. Lymph-node locations and sites of infection are positioned randomly. The figure shows the number of effector T cells in the system over time. Their population increases rapidly in the beginning of the run, when the tissue environment is filled with sites of infection. This demonstrates that scouting DCs are able to reach lymph-node locations and report their samples.

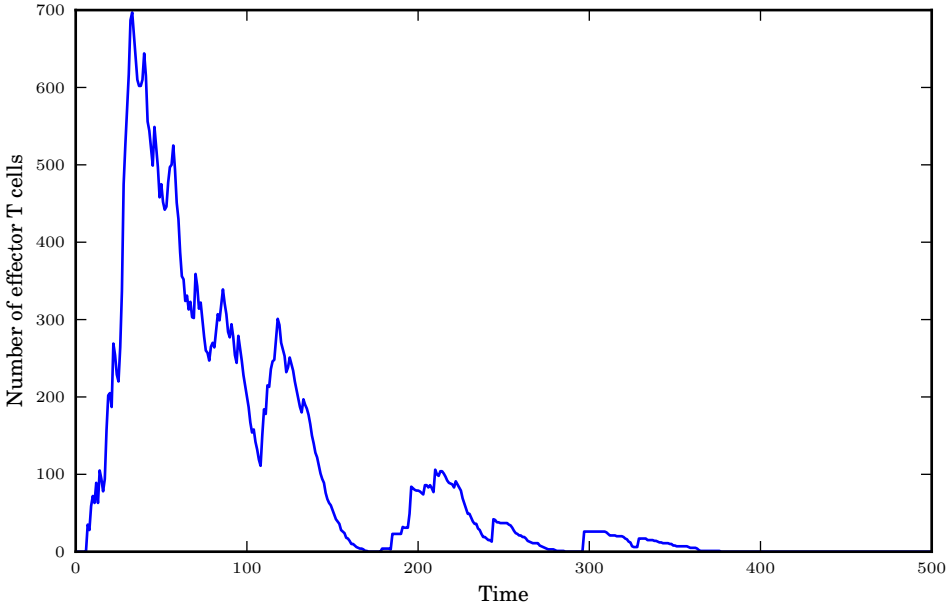


FIGURE 5.11: Increasing number of effector T cells confirms reporting function in DCs.

System Response

The ability of the system to respond is tested by monitoring the total level of infection. Results from an example run are presented in figure 5.12, using the input parameters of table 5.5. As before, lymph-node locations and sites of infection are positioned randomly. The figure shows that the level of infection drops with time, reaching zero at around 300 seconds. For comparison, results from an identical run where gradients are disabled are also given, illustrating the importance of guided movement in the system.

5.4 Reflection on Probing Biology for AISs

The immunological research literature on DC biology reveals a more complicated picture than 'textbook' immunology in which the DC is far from becoming fully characterised. Many aspects of the DC life cycle are still unclear and new questions are being raised as new evidence come to light. Surveying the DC literature

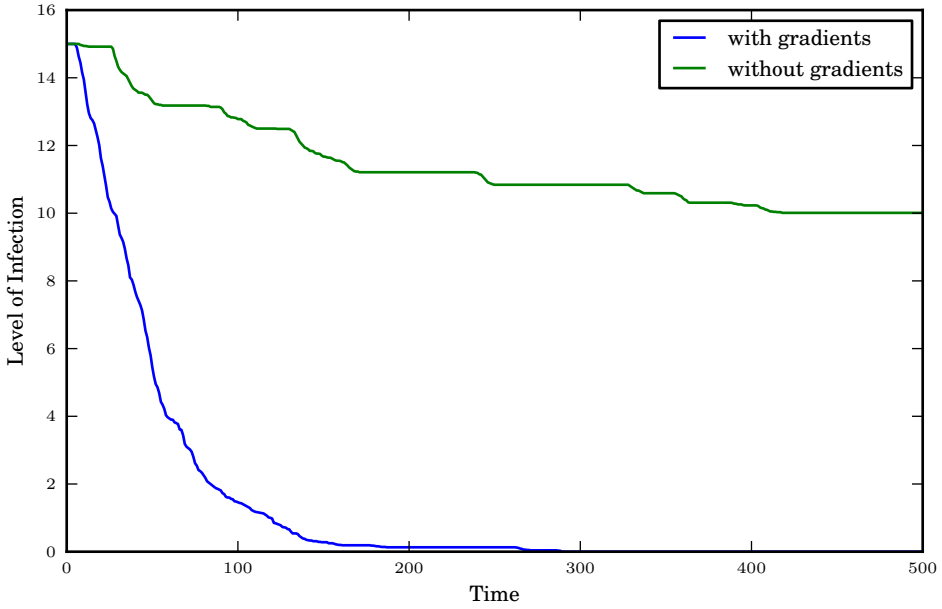


FIGURE 5.12: Decreasing level of infection demonstrates system response, which is enhanced by the presence of gradients.

with the intention of identifying concepts for exploitation within biologically inspired computing can be hard due to a combination of unsettled, and often ambiguous, immunological parlance, molecular detail, and the enormous complexity of the subject itself. For that reason, it is worth considering the research dimensions of figure 5.1 to facilitate the process of immune probing within AISs. To illustrate this point, the discussion of section 2.4.2.3 is revisited, concerning an example case found in the AIS literature review where DC function is misunderstood.

In [91] a distributed misbehaviour detection system for a MANET routing protocol is proposed, modelled after the behaviour of DCs and inspired by the danger theory. For the purpose of this discussion, the theoretical context is of lesser importance; the interest lies on the underlying biological process that is exploited. According to the authors, the biological process modelled is the following: DCs sample antigens from body tissues; depending on the types of signals present in the residing tissue, immature DCs differentiate into a mature or semi-mature

state; either state enables DCs to migrate to the thymus and present the sampled antigen for T-cell maturity; the effect each DC state has on the T cells within the thymus is either immunogenic, mature DCs initiating T-cell effector functions that lead to an adaptive immune response, or tolerogenic, semi-mature DCs causing T-cell de-activation and therefore leading to suppression of immune response.

The above description of DC functionality mixes up two distinct immune processes, each involving different DC subsets. One is related to the selection process of developing T cells, as they get educated within the thymus with the help of thymic DCs. The other process is associated with the popular model of T-cell priming or tolerance within SLOs, promoted by differentiated tissue-resident DCs. Although the immunological literature does not entirely exclude the possibility of the thymus being a destination organ of DCs migrating from the periphery, it is made clear that this scenario is blocked in the case of inflammation-triggered DC maturation.

In particular, the first process is the thymic selection of T cells that supplies the population of mature naive T cells circulating in the lymphatics. Thymic selection involves positive and negative selection of developing T cells from thymocytes within the thymus [72, p. 251–257]. DCs present self-antigens during negative selection [72, p. 289–293]. However, the DCs involved are a distinct subpopulation, known as thymic dendritic cells, which have been studied very little compared to DCs in the periphery [74]. According to recent immunological opinion, the peripheral population of tissue-sampling DCs fulfil a very different role: they home to SLOs to present peripheral tissue-derived antigen under either steady-state or inflammatory conditions and, if the right conditions are present, prime an immunogenic effect.

Due to limited studies on the subject, contradictory speculations are found in the literature concerning the question of whether the thymus is an additional destination of DCs migrating from the periphery. For example, according to

Alvarez et al. [6] the thymus accommodates two distinct populations of DCs, one developing from precursors within the thymus and a second originating from the periphery. It is suggested that T-cell tolerance within the thymus is promoted via antigen presentation by either DC subset. Randolph et al. [110], however, express doubts as to whether DC trafficking to the thymus from other tissues occurs at all and indicate that, even if it happens, it is unlikely to be related with presentation of self-antigens and clonal deletion of lymphocytes. As for homing of inflammation-induced mature DCs to the thymus, Alvarez et al. [6] state that such capability is selectively blocked so as to prevent accidental removal of developing T cells that recognise pathogen-associated antigens.

To summarise, it is inevitable that the AIS practitioner will focus on only a small aspect of the immune system and that during abstraction there will be simplifications. Nonetheless, it is important to obtain an understanding of the context, as knowledge about the generic immune functionality can prove valuable in case details of the selected aspect are revisited in order to refine the corresponding AIS or further probing into related mechanisms is decided in order to extend the original AIS. Misconceptions can be avoided if immune mechanisms are examined within the context of the research dimensions outlined in section 5.1.1. The immune system operates in a distributed manner by deploying immune cells to build up its responses, but immune cells alone are not enough to fully describe the story. The physiological infrastructure that supports the development, education and operation of immune cells is also critical to immune function, and plays an important role in enabling immune cells to carry out the observed immunological responses.

5.5 Conclusion

This chapter has explored the behaviour and functionality of DCs with reference to the anatomy, physiology and conditions of the immune system. Through

surveying the current immunological literature on the subject, an outline that captures the basic phases in the life cycle of a DC was composed. In addition, an agent-based model was developed founded on the high-level functionality of immunogenic DCs, in an attempt to capture key aspects from the DC life cycle in simulation. The above results are utilised in the next chapter, which examines the development of an AIS within a specknet.

Chapter 6

Development of an AIS within Specknet

6.1 Introduction

The goal of this chapter is to investigate the second research question of this thesis, relating to the idea that having an engineered system, such as a specknet, facilitates the process of developing novel AISs. More specifically, a simple instance of a problem involving temperature monitoring and control by a specknet is examined within a simulation environment. Such an application scenario is common within WSNs and associates well with the self-regulating nature of the immune system. The AIS in development is based on the basic model of DC life cycle and the ABM from chapter 5, and is used for sampling the specknet.

In particular, section 6.2 introduces the application problem. In section 6.2.1, the study framework for specknets is instantiated for the selected application problem. Section 6.2.2 explains the features of the application problem with respect to the properties for future AISs mentioned in section 1.1, followed by a brief discussion on simulation in section 6.2.3. Section 6.3 provides a detailed description of the application system, including mapping in 6.3.1, implementation

in 6.3.2 and system parameters in 6.3.3. In section 6.4, the specification of the application problem is given. Results from experiments testing the system are presented in section 6.5, followed by conclusions in section 6.6.

6.2 Application Problem

Monitoring of environmental phenomena is a characteristic class of applications within WSNs [147], although the exact details vary widely depending on the problem instance. For example, monitoring is frequently met in the literature in environmental projects that involve event detection or periodic measurement of a variety of factors [113]. In this thesis, the type of application chosen for experimental study is a typical WSN application, a control problem relating to monitoring of temperature by a specknet. In particular, the problem description is the following. A network of specks attempts to configure the temperature of the environment, wherein it is situated, to levels that are desirable throughout the network, through the controlled operation of air conditioning units (ACUs).

It should be noted that all experiments are performed using a simulation tool. Although only approximating the physical world, simulation allows for easy adjustment of a specknet's parameters and trouble-free configuration of specks' characteristics at the physical and data link layers. In addition, configuring the environment through spots of constant or variable temperature and controlling the effect of ACUs is a straightforward task.

6.2.1 Study Framework Instantiated

Recall the study framework for specknets of figure 3.6 which describes four main aspects to the operation of a specknet, namely the components of data collection, processing, decision making, and response. With reference to this framework, the function of the specknet under the temperature monitoring problem is outlined

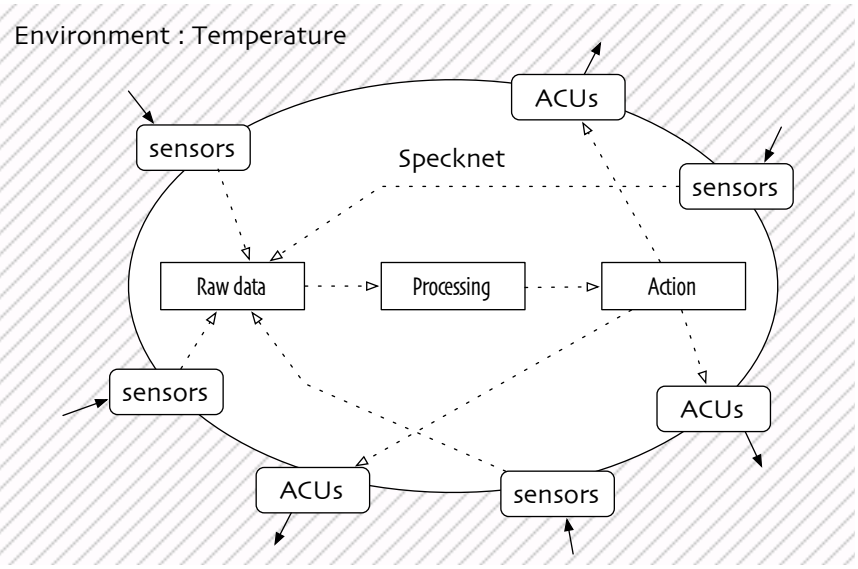


FIGURE 6.1: The study framework for specknets of figure 3.6 instantiated for the application problem of temperature monitoring and control.

in figure 6.1. Specks sense temperature data which are collected to local sinks that make decisions. If necessary, actions control ACUs in order to manipulate the temperature of the environment.

With regard to the immune system, of the four framework components only data collection is considered in detail, by referring to the migratory functionality of DCs, as explained in section 4.5. The remaining components of processing, decision making and action are not examined from an immunological perspective as part of the application problem, although they could be subject for immunobiological consideration. These have been discussed from a theoretical perspective in juxtaposition with co-respondence from the CIS back in chapter 4. However, certain anatomical features that became apparent in the modelling exercise of section 5.3, such as the peripheral tissue and the lymph node, are taken into consideration for the organisation of the specks.

6.2.2 Features

Examined within the specknet environment, the selected application problem is deemed to satisfy a number of desired properties for future AISs, see section 1.1.

Firstly, the application problem provides the background for achieving *embodied* AIS. Stepney [121] describes embodiment as a "rich complex feedback process" arising from "the coupling between the computational system and its environment." Design principles necessary for embodiment suggested by Stepney include: interaction between the system and its environment on timescales that are varying and much slower than typical virtual ones; constant update of input data by the system without requiring explicit request; capacity of the system to alter the state of its environment. All these are present in the chosen case study; interaction between the specknet and its environment is governed by the rate of change of temperature, the specknet's sensory tasks are not guided externally, and the specknet has the ability to change the temperature of its environment via actuators.

The problem of monitoring is compatible with another desired property, that of *life-long learning*. Optimising the temperature of the environment to be in line with the temperature configuration desired by specks is an ongoing process rather than a one-off solution. The specknet is required to achieve and maintain a certain temperature profile for its surroundings for as long as it is up and running, by prompt reaction to environmental changes and, ideally, learning of and so adapting to any recurring situations.

6.2.3 On Simulation

There are a number of simulation tools available for WSNs, the majority of which are discrete event driven, as time-driven types run in real time and, therefore, do not allow customisation of execution time. The most common tests performed

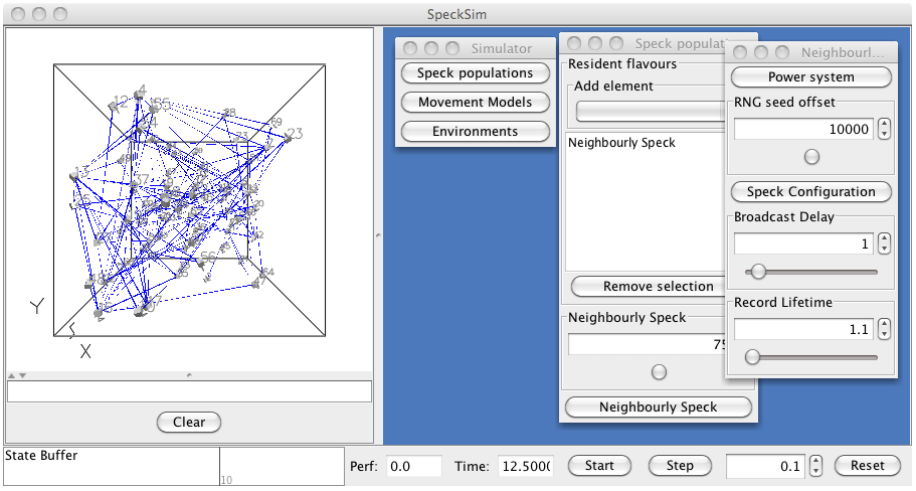


FIGURE 6.2: SpeckSim, an event-driven Java simulator for specknets.

in the WSN literature relate to communication and network protocol studies, followed by application-dependent scenarios that involve instruction-level simulation, that is, actual device code for a specific platform is executed. A survey on WSN simulation tools can be found in [47].

The simulation software used for the development and evaluation of the case study is SpeckSim [92], see figure 6.2. SpeckSim is an event-driven simulator implemented in Java, which offers a behavioural simulation environment for specknets. It also incorporates a number of network-level features. Similar to other WSN-specific simulation tools, SpeckSim includes generic energy consumption, movement and environment models, in addition to typical network components, such as radio and broadcast models. The model of a speck provides the typical functionality of a sensor device operating on battery, while specks of different types are allowed, that is, heterogeneous networks are supported.

6.3 System Description

This section provides a detailed description of the application system. The specifics of the AIS aspect of the system are explained, as well as implementation issues related to the engineering side of the system. Table 6.1 summarises

Immune elements	**In the specknet**	**In the application problem**
Biological Level		
Dendritic cell:	Data radio message	Scouting message
Generation:	Radio transmission	Radio transmission
Bone marrow:	N/A	N/A
Circulatory system:	N/A	N/A
Peripheral tissue:	Sensor node	Temperature sensor speck
Tissue sampling:	Scouting: Addressing Neighbourhood	Walk: Random
Migration:	Conditional	Basic / Only triggered / All except suppressed
Lymphatics:	Routing	Minimum cost forwarding
Lymph node:	Sink	Integration speck
Theoretical Level		
Co-respondence:		
Integration	In-network processing	Assess confidence / Voting
Decision-making	In-network processing	Mean error state
Action	Response	Regulate ACU

TABLE 6.1: Mapping points between immune aspects (elements and processes) of focus and the specknet, in context of the application problem of temperature monitoring and control.

the mapping points between the immune aspects of focus and the engineered system in the context of the temperature monitoring application problem. These are grouped according to the biological and theoretical levels, as discussed in section 2.3.3. Each of the mapping points is examined in detail in the sections that follow.

6.3.1 An AIS for Specknet

This section examines how to adapt the model of the lifecycle of a DC of figure 5.6 for developing an AIS related data collection within the specknet environment.

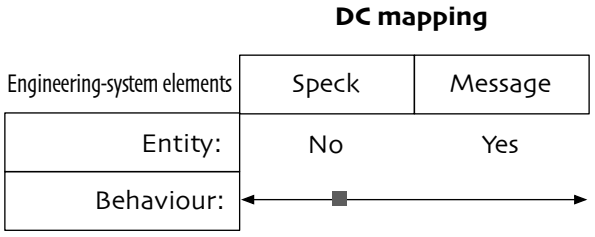


FIGURE 6.3: Representation options of a DC within specknet. As an entity, a DC can be mapped to a speck or a message. In terms of behaviour, the mapping of a DC can slide between both elements of the engineering system.

6.3.1.1 Dendritic Cell Mapping

Perhaps the most important question at this stage is how the DC is represented within the network. Two options become immediately apparent, see figure 6.3. The first is to map the DC to the speck. The second is to map the DC to the data message. Considering the generic features of a DC in brief, it is an individual mobile unit with distinct behaviour and states, which may die but is replaceable with similar units.

A speck is a single unit, which can also be potentially mobile, although intentional movement is hard to achieve mechanically at such small scale. Firmware provides the speck with programmed functionality that can be reprogrammed, albeit at great engineering cost. Specks are highly likely to become permanently incapacitated, either due energy depletion or environmental factors. Energy depletion can be overcome with hardware alterations that support energy renewal. Physically, though, such solutions greatly limit the number of operations a speck is able to perform over time, especially related to communication. Another option is replacement with additional units, which can also mitigate the situation of damage by external factors. This, however, is a manual solution.

A data message is a way of information transfer, but it is not necessarily a *single* entity. With the majority of communication performed over radio, messages are subject to the rules that govern network communication via a shared medium (broadcast). As a consequence, a single data message leaving the source speck

may be heard by more than one speck, meaning that upon reception the original message will be multiplied to several (largely) identical copies. However, it is possible to ensure unique destination specks for transmitted data message, achieving thus deliberate movement. Regarding functionality, the behaviour of a data message can be encoded to rules that exist either entirely within the message or the speck, or are shared between the two. The more independent the data message design is from specks, the greater the infrastructure required to support agent-like message implementations becomes. At the other end of the spectrum, specks become responsible for handling the messages, which become smaller and, thus, less expensive to move around. Last, the number of data messages within a specknet can be considerably larger compared to the number of specks, but it is easily adjustable.

Due to the flexibility provided by a data message in terms of movement, functionality and numbers over those of a speck, the decision is made to represent the DC with the data message. In terms of behaviour, the DC is largely implemented on the side of the speck.

6.3.1.2 Life Cycle of a Data Message

To trace the life cycle of the data message in the context of the temperature monitoring problem, the model of the DC life cycle is reviewed, see figure 6.4. In the basic model of section 5.2.5, the DC originates at the bone marrow and from there migrates via the blood circulatory system to periphery. In the specknet, the generation of the data message effectively takes place whenever a speck has captured sensory data about the temperature state of the environment. The anatomical complexity involved in the stages that precede the arrival of the DC to the peripheral tissue is deemed superfluous in the context of the application problem. For this reason, from the initial three components of the DC model only the first is represented. This leads to the first stage in the life cycle of a data message, generation at *sensor speck*.

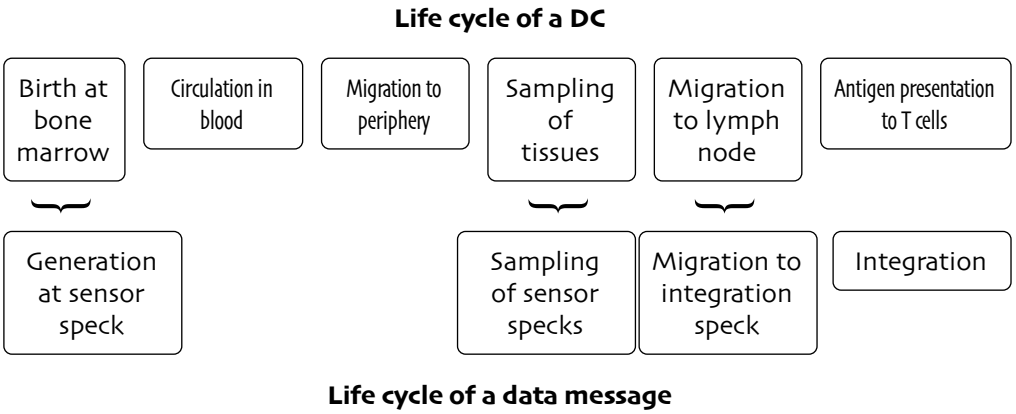


FIGURE 6.4: Life cycle of a data message alongside the basic model of the DC life cycle from section 5.2.5.

The next two stages in the DC model involve two different anatomical elements, the peripheral tissue sampled for antigenic material and the lymph node where this material is being presented. In the specknet, temperature data are provided by the sensor specks which places them into a role analogous to that of peripheral tissue. Sensor specks are also responsible for determining what the desired levels of temperature are. As for the role of the lymph node, a new type of speck is defined, the *integration speck*, which is responsible for acting as an in-network sink, receiving and integrating the data delivered by data messages. As such, the next two stages in the lifecycle of a data message are sampling of sensor specks and migration to an integration speck. Conditions that can trigger migration of a data message are based on the DC functional model of figure 5.5.

The final stage in the DC model is antigen presentation to T cells. Rather than being mapped explicitly, this stage is instead translated into a process of integration. This process uses the information reported by data messages that have made it through to an integration speck for evaluating whether the desired temperature state of sensor specks is met. To create a complete feedback loop, an integration speck is then responsible for choosing to alter the temperature of the environment by controlling the corresponding ACU.

Last, it is important to specify the composition of the specknet. For example

are all specks identical or are they of distinct types? If specks are divided into subpopulations, then is the differentiation limited to the software level or does it extend to the hardware? These decisions clearly have great impact on the engineering side of the system, as different configurations can lead to entirely different sets of requirements. In the application system, it is assumed that the sensor speck and the integration speck are two distinct types of device, simply by analogy to the peripheral tissue and the lymph nodes found in the body.

6.3.2 Implementation Details

This section describes details of the monitoring system as implemented in SpeckSim, in terms of both the engineering aspect of the system and the AIS method applied. The specknet consists of two types of speck devices, sensor specks and integration specks. The difference between them is that sensor specks can measure temperature and map to tissue, whereas integration specks are able to control ACUs and map to lymph nodes. ACUs are co-located with integration specks. Figure 6.5 illustrates the ways in which specks communicate with each other. Each of these cases is explained in the paragraphs that follow.

6.3.2.1 Supporting Services

During initialisation of a simulation run, all specks power up at random times and set up the supporting services: neighbourhoods and routing paths.

Neighbourhood Creation

To handle the situation of an individual data message multiplying during sampling, discussed in section 6.3.1.1, a sensor speck needs to be able to transmit to a specific recipient, also known as unicasting. For a sensor speck to be able to

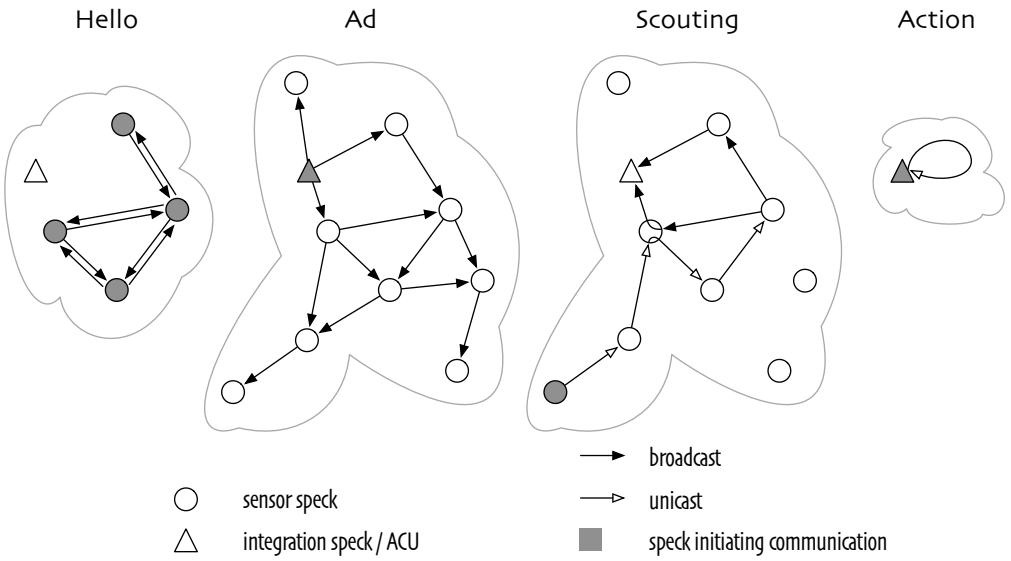


FIGURE 6.5: Illustration of messages communicated within the monitoring system, as implemented in SpeckSim. Four types of radio messages are used: `Hello`, `Ad`, `Scouting` and `Action`. For a summary, see section 6.3.2.3.

unicast a data message, it requires knowledge about specks in the vicinity. This is achieved with the help of neighbourhoods, see section 3.5.

The method used by sensor specks to form one-hop neighbourhoods is basic and commonly found in the WSN literature. Sensor specks periodically exchange `Hello` messages that contain an identification number (ID) which characterises each sensor speck, see figure 6.5. Whenever a sensor speck receives one such message, it creates a new transient record or updates the corresponding entry in the table of neighbours it maintains locally. The IDs are provided by the simulator, that is no specific algorithm is implemented for assigning addresses to sensor specks. Given that the neighbourhoods have a size of one-hop, the requirement for the IDs to be unique applies only locally. Integration specks do not participate in neighbourhood formation.

Routing Paths

Delivery of data messages to integration specks requires support at the network layer. This is done through the deployment of a routing protocol. Construction

of routing paths used to guide migrating data messages is initiated by integration specks. A tree-based routing protocol for large sensor networks is used [146], which is comparable to the chemical gradients and lymphatic vessels used by DCs to reach lymph nodes. The algorithm relies on the notion of a cost maintained at each node participating in the tree. The cost value is disseminated via `Ad` messages and is used to forward data to a sink (the root of the tree), see figure 6.5. The routing protocol includes the following features. Firstly, no forwarding path states are needed. Each sensor speck only needs to maintain the minimum cost from itself to the sink. Secondly, once the cost field is set up, any sensor speck can deliver data to the sink. Last, intermediate sensor speck do not need an ID during forwarding.

The selected routing protocol relies on broadcasting of messages by forwarding sensor specks, which means that multiple copies of a data message may be forwarded to an integration speck. To ensure only unique copies are received by integration specks, data messages contain a unique identification (UID) field. The field consists of two values, a sequence number and a time stamp. These are assigned by the sensor speck that first decides to route the data message to an integration speck. Although this technique does not entirely guarantee unique identification, the possibility of two different data messages being assigned identical UID values within some time is quite low. Aside from the above side effect of broadcasting during routing of data, the protocol uses simple operations, is scalable and there is no need to dynamically update costs.[1]

6.3.2.2 Immune Functionality

Generation Sensor specks are responsible for initiating transmission of the data messages that map DCs, named `Scouting` messages, see figure 6.5. These are generated periodically by each sensor speck, with the time of initial generation randomised across sensor specks. A newly generated `Scouting` message is

[1] Unless optimal cost values are required.

assigned a fixed path-length value $h_{pl} \in \mathbb{Z}^+$ that corresponds to the number of samples it needs to collect from sensor specks. In addition, it contains a time-to-live (TTL) field that determines the maximum number of nodes h_{ttl} it can visit to complete its walk:

$$h_{ttl} = h \times h_{pl}, h > 0 \text{ and } h_{ttl} \in \mathbb{Z}^+ \tag{6.1}$$

where h is a coefficient supplied by the sensor speck. If the `Scouting` message reaches the TTL without having collected all the samples, it is dropped. Use of a TTL field is common for messages that perform open-ended walks in a network to avoid boundless relay in case they fall into circular paths.

Sampling The samples that a `Scouting` message collects are stored in a table of counters of fixed size:

$$S = \{s_1, s_2, \ldots, s_k\} \tag{6.2}$$

with k being the number of possible error states E a sensor speck can be in:

$$E = \{\frac{-k+1}{2}, ..., 0, ..., \frac{k-1}{2}\}, k \text{ is odd} \tag{6.3}$$

Each sensor speck reports how hot or cold it is, based on its sensor readings and the temperature that it expects to measure. To perform an update to a sampling `Scouting` message, a sensor speck calculates the signed difference $T_d \in \mathbb{R}$ of its desired T_D from its estimated T_m temperature:

$$T_d = T_m - T_D \tag{6.4}$$

It, then, maps T_d to an ordinal value $e \in E$, which is used to update the corresponding counter in the table of the `Scouting` message. By pre-processing raw

temperature measurements, the size of the `Scouting` message is reduced significantly, therefore lowering the impact that sampling has on the power consumption of sensor specks.

The walk of a `Scouting` message is characterised by the selection process of the next sensor speck candidate for sampling. Selection can be random or probabilistic involving various criteria which, however, may require sensor specks to have additional knowledge about the state of their neighbours; for example, for `Scouting` messages to perform power-aware walks, sensor specks need to have information about the available energy of their neighbouring sensor specks. In the system, the `Scouting` message performs a random walk taking one sample per visit from a sensor speck, but within a single walk it can collect several samples from multiple visits to a particular sensor.

Migration After an update of its table of samples, the `Scouting` message may either continue gathering samples, or stop sampling and start the process of migration to an integration speck. Conditions that can trigger migration are based on the DC functional model of figure 5.5:

$$\frac{1}{u}\sum_{n=1}^{u} s_n > v_{msg\_threshold}, u <= h_{pl} \tag{6.5a}$$

$$|\frac{1}{z}\sum_{n=1}^{z}(m_t - m_{t-1})| > v_{speck\_threshold} \tag{6.5b}$$

$$u = h_{pl} \tag{6.5c}$$

where z is the number of differences calculated from the most recent sensor measurements and u is the number of samples collected so far by the `Scouting` message. Equations 6.5a and 6.5b represent the idea of a mature DC in the well-studied model, which assumes maturation requires encounter with inflamed tissue. Hence, the decision to trigger migration relies upon threshold values $v_{msg\_threshold}$ and $v_{speck\_threshold}$, which are used to evaluate: in the case of equation 6.5a, the level of accumulated error the `Scouting` message has sampled so far; in the case

of equation 6.5b, the rate of change in the measurements a sensor speck captures. Alternatively, equation 6.5c represents the idea of decoupling maturation from migration. Under this condition, the `Scouting` message starts migration upon completion of its walk with probability p, similar to a DC migrating in the steady state.

When a `Scouting` message begins migration, the sensor speck that provided the last sample update becomes the first sensor speck that routes the message towards an integration speck. During this transition, the `Scouting` message is supplied from the sensor speck with information necessary for routing via the tree-based protocol and for UID validation at the integration speck. Since migration is guided by a tree structure, no TTL field is included in the migrating `Scouting` message.

Integration When the integration speck receives a migrating `Scouting` message, it first examines whether it has already processed another copy of this message, by comparing its UID against the local history. If the UID is unique, then the received `Scouting` message is added to a buffer of size s_b, otherwise it is dropped. Messages are stored in the buffer for a limited time t_b.

After a buffer update, the integration speck assesses its *confidence* in the stored data. To do so, it examines whether the reception rate of the stored `Scouting` messages is within a pre-specified threshold r_{Rx}. If so, the integration speck then estimates the reported error state $e_{mean} \in E$ of the sensor specks by running a simple voting algorithm, that is by taking the mean over the stored error samples.

Decision-making and Action The integration speck decides whether to act depending on the resulting state value e_{mean}. If $e_{mean} \neq 0$, the integration speck adjusts the temperature effect of the nearby ACU, by communicating an `Action` message, see figure 6.5. The message carries the magnitude of change required. This is defined by mapping e_{mean} back to a temperature step T_{step}.

6.3.2.3 Summary of Message Types

There are four message types used within the specknet, see figure 6.5:

`Hello:` These messages are communicated by sensor specks locally (over one-hop distance) to exchange neighbourhood information. They contain the ID and the battery level of the source.

`Ad:` Broadcast of these messages is initiated by integration specks and are further relayed by sensor specks to establish a cost field for forwarding data. They contain the routing cost to the integration speck that initiated the round of broadcast.

`Scouting:` These are the messages that represent DCs. They are generated by and gather samples from sensor specks. They report the data that they collect to integration specks.

`Action:` These messages carry an instruction signal sent by an integration speck to its corresponding ACU.

6.3.3 Parameters

The parameters of the system can be grouped into two categories, depending on the domain from where they originate. For instance, adjusting the value of the TTL field in a `Scouting` message is of practical requirement that stems from the networking nature of the engineered system. On the other hand, the number of sensor specks that a `Scouting` message is instructed to sample is a parameter that can be traced back to the biological model, as it is associated with the lifespan of a DC, see table 5.2. Table 6.2 lists the main parameters of the system, grouped into those coming from engineering and those that are AIS related.

System parameters	
Engineering related	
Neighbourhood:	radio range, transmission rate of `Hello` messages, lifetime of received neighbour data
Routing:	transmission rate of `Ad` messages, backoff timer coefficient, increase budget coefficient
Sampling:	TTL coefficient h
AIS related	
Generation:	transmission rate of `Scouting` messages, path length h_{pl}
Sampling:	error states k
Migration:	triggering thresholds $v_{msg\_threshold}$ and $v_{speck\_threshold}$, suppression probability p
Integration:	lifetime of received `Scouting` message data t_b
Action:	step change T_{step}

TABLE 6.2: Main system parameters, grouped into engineering and AIS related.

6.4 Problem Specification

The application problem is defined as follows. A specknet consists of specks B:

$$B = \{p_1, p_2, \ldots, p_n, q_1, q_2, \ldots, q_r\} \tag{6.6}$$

where $p_n \in B$ is of type sensor speck and $q_r \in B$ is of type integration speck. Each speck occupies a position (x, y) on a 2D plane and is configured with generic models of microcontroller, modem and battery. The radio model used is perfectly spherical and reliable, and allows communication between specks that are located within distance $d < d_{range}$, where d_{range} is the maximum radio range.

Sensor Each sensor speck p_i has a temperature sensor that follows a generic sensor model given by the measurement function:

$$m = c \times v + b + N(0, \sigma) \tag{6.7}$$

where m is the measured temperature value, c is a scale factor supplied by the sensor manufacturer, v is the true temperature, b is the sensor bias and $N(0, \sigma)$ is the sensor noise, following a model of gaussian distribution around zero. Low-pass filtering is performed in order to reduce noise by calculating an estimate $\hat{v}$ from the measured values, specifically a moving average $\bar{v}$. For further calculations, value $\hat{v}$ is used thereafter.

ACU Each integration speck q_j is attached to an ACU R. A control message from the integration speck informs the ACU about the adjustment required to apply to its temperature effect. The effect can be positive, negative or none. Changes in the ACU's temperature take effect instantaneously.

Temperature Model Temperature is modelled as a time varying scalar field. The temperature environment can be affected in two ways, by the presence of hot spots H and by active ACUs. The true temperature of the environment at the position of a speck, T_P, is given by the function:

$$T_P = T_A + \sum_{i=0}^{q} w_H \times e_H + \sum_{j=0}^{r} w_R \times e_R \tag{6.8}$$

where T_A is a constant representing the ambient temperature of the environment and w is the weighting function of the effectors that controls the drop off of their effect e over distance D:

$$w = \frac{1}{\|l \times D\|^2 + 1} \tag{6.9}$$

with l being the scaling factor of the effect. Specks are assumed to be static, so the weighting function remains constant. The effect of a hot spot at any time

point is given by a piecewise linear function:

$$C = \{(t_0, T_0), ..., (t_n, T_n)\} \tag{6.10a}$$

and is defined by a set C of tuples of time and temperature.

Metrics In order to evaluate the response of the system, the following metrics are defined:

- **root mean square error (RMSE)**: evaluates the ability of the specknet to maintain temperature.
- **energy expense**: evaluates the power consumption of the specknet during its attempt to maintain temperature.

To be able to evaluate the quality of the AIS solution, two bounds are defined: the *baseline* and the *optimal solution*. The baseline marks the temperature error of the system when no responsive mechanism is activated. The optimal solution is approximated by using a traditional optimiser, the least squares method, implemented outside the simulator in Python.

6.5 Experiments and Results

Restating the goal of this chapter, the aim is to explore whether utilising a specknet alongside AIS development is of benefit to the exploration process of the AIS. For this reason, this section investigates only a subset of the system parameters, rather than performing an in-depth exploration of the entire parameter set. As noted in section 6.3.3, the system parameters fall into two categories. Those coming from the engineering side are discussed in section 6.5.3, while those related to the AIS method are examined in section 6.5.4. Firstly, though, section 6.5.1 provides an example application scenario, and section 6.5.2 summarises the general

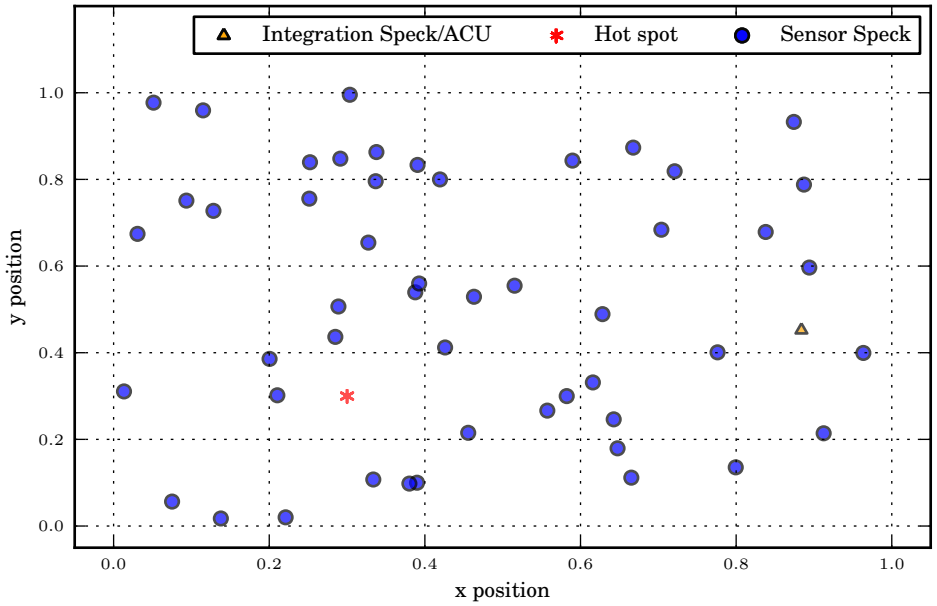


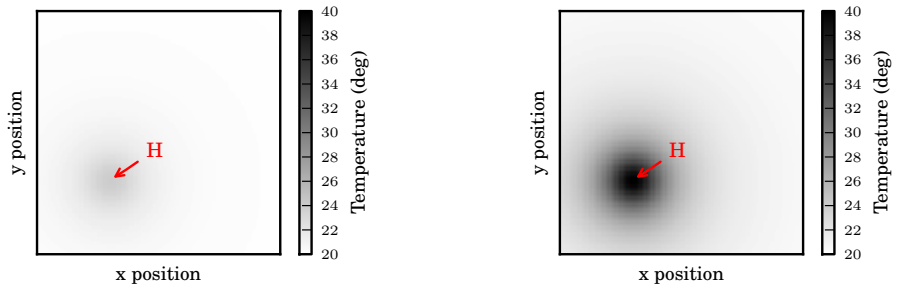
FIGURE 6.6: Scatter plot of example scenario showing positions of the simulated elements: specks, an ACU and a single hot spot.

settings of SpeckSim and the specknet composition used throughout the experiments.

6.5.1 Example Scenario

This section illustrates an example scenario on a basic specknet set-up. The specknet consists of 50 sensor specks and one integration speck, all randomly deployed within the unit square as shown in figure 6.6. There is one ACU that is co-located with the integration speck. The environment contains a single hot spot of variable effect: $C_H = \{(0, 0), (10, 4), (50, 20)\}$, positioned in a random location. The desired temperature of sensor specks matches the ambient temperature at $T_D = T_A = 20$ degrees.

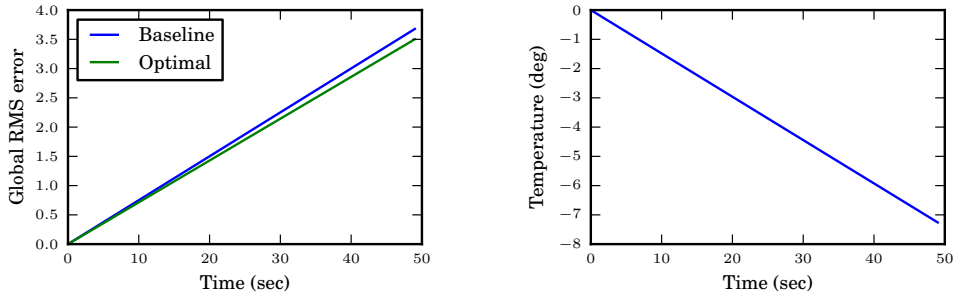
Figures 6.7(a) and 6.7(b) show the temperature map of the unit square, as affected by the hot spot only, at time points 10 seconds and 50 seconds respectively. The greater the temperature of hot spot H, the darker the area becomes around it.



(a) Time 10 sec

(b) Time 50 sec

FIGURE 6.7: Temperature maps of example run at time points 10 seconds (a) and 50 seconds (b), containing a single hot spot of variable temperature.



(a) RMSE bounds

(b) Optimised action for ACU

FIGURE 6.8: Approximation of optimal solution of example run using the least squares method. Figure (a) shows the baseline and optimal RMSE lines. Figure (b) shows the temperature that the ACU in the specknet needs to be at in order to achieve the optimal RMSE result of figure (a).

Figure 6.8 shows the results of applying the least squares method to the example set-up. The optimal line in 6.8(a) represents the minimum RMSE over time found by the optimiser, which can be achieved if the ACU is configured to respond in the manner described by figure 6.8(b). The baseline in 6.8(a) represents the worst-case scenario, when the ACU in the specknet is disabled.

6.5.2 General Settings

In SpeckSim, a specknet is deployed on a two-dimensional surface of unit square. At the start of a simulation run, specks power up at varied times and remain static

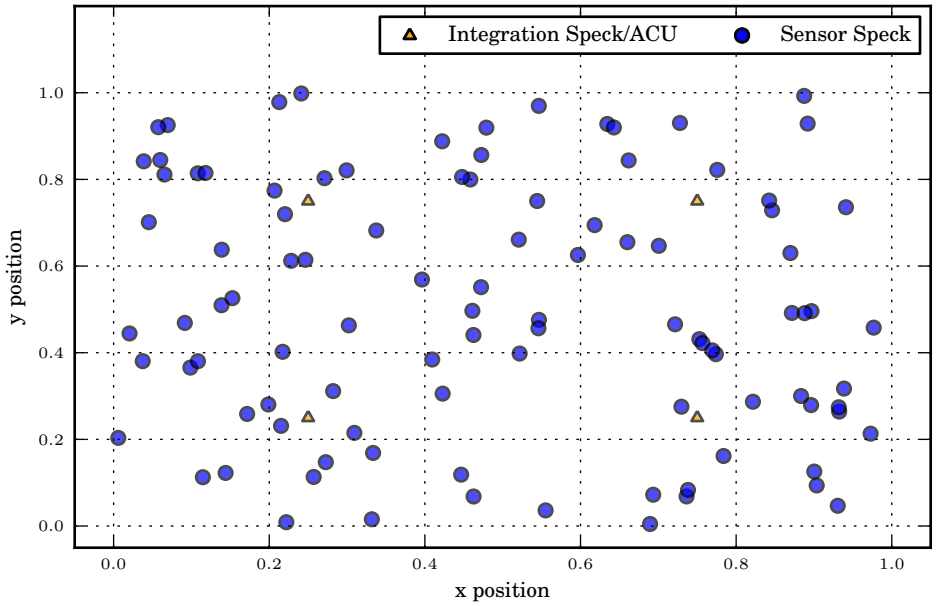


FIGURE 6.9: Scatter plot of positions of 100 sensor specks and 4 integration specks/ACUs.

throughout the run. All specks are powered by the same battery model[2] and run with the default microcontroller configuration. Radio is modelled as a perfect spherical shell and communication is performed using a carrier sense medium access control (MAC) protocol of maximum backoff 1.0 second and transmission time 3.0 seconds. All sensor specks sample temperature at a rate of one sample per 0.2 seconds, with noise $N(0, 0.6)$ and no bias. They share a fixed desired temperature value $T_D = 20.0$ degrees.

The specknet set-up on which all experiments run has 100 sensor specks[3] of random layout and average separation of 0.1 units, and 4 integration specks each placed at the centre of a different quarter of the unit square. The number of ACUs is also 4 and they are placed in the same locations as integration specks. Figure 6.9 shows the layout of the specknet. Table 6.3 summarises the general settings used in the simulator.

[2]The battery model selected is CR2032.
[3]An indicative number of medium-sized sensor networks.

About	*Description*	*Value*
Deployment:	Surface size	unit square
Radio:	CSMA maximum backoff	1 sec
	CSMA transmission time	3 sec
Sensor:	Noise	$N(0, 0.6)$
	Bias	none
	Sampling rate	0.2 sec
Application:	Sensor specks:	100
	Integration specks:	4
	ACUs R:	4
	Layout of sensor specks:	Random with average separation 0.1 units
	Position of integration specks/ACUs:	Each pair at the centre of a unit-square quarter
	Desired temperature T_D	20 degrees

TABLE 6.3: General settings used in SpeckSim.

6.5.3 Parameters Related to Engineering

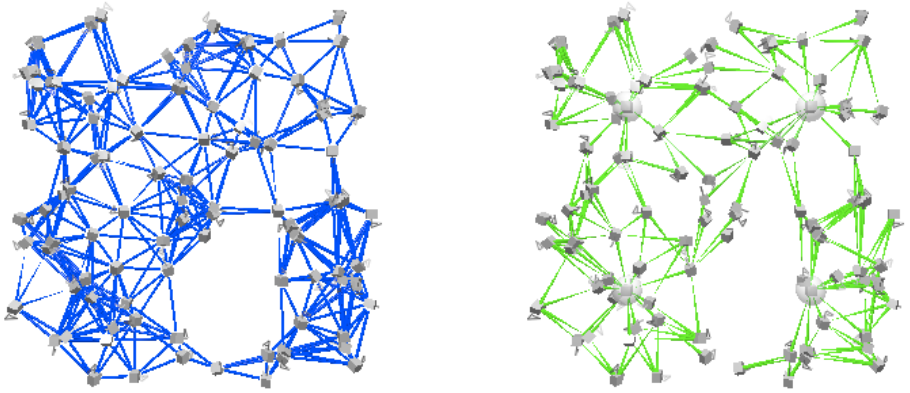
Parameters related to engineering are treated as a set of technical requirements, because they are associated with the services necessary for supporting the implementation of the AIS within the specknet environment, as discussed in section 6.3.2.1. They are primarily related to neighbourhood formation and routing, and they are tuned to fulfil the following requirements.

To allow a `Scouting` message move between sensor specks during sampling, it is assumed that these specks are fully connected. This requirement is met by adjusting the density of the network using a radio range of 0.2 units, resulting in a mean neighbourhood size of 10. Similarly, for a `Scouting` message to be able to report its collected data to an integration speck, it is necessary that there is at least one route linking each sensor speck in the network to an integration speck. This is achieved by setting accordingly the routing coefficients, to 0.1 for the backoff timer and 0.3 for the budget increase.

With regard to the frequency of the `Hello` and `Ad` messages, the requirements are less strict. Specks remain static, so changes in the neighbourhoods can only

About	*Description*	*Value*
Neighbourhood:	Radio range d_{range}	0.2 units
	Transmission rate of `Hello` messages	1 sec
	Lifetime of received neighbour data	1.1 sec
Routing:	Transmission rate of `Ad` messages	occurs once
	Backoff timer coefficient	0.1
	Budget increase coefficient	0.3
Sampling:	TTL coefficient h	1.5

TABLE 6.4: Main input parameters related to engineering.



(a) Neighbourhoods (b) Routes

FIGURE 6.10: SpeckSim snapshots showing: in figure (a) neighbourhood links between sensor specks and in figure (b) routing links leading from sensor specks (cubes) to integration specks (spheres).

happen due to battery depletion. Therefore `Hello` messages are exchanged at a nominal rate of 1 sec and the neighbour data are refreshed every 1.1 sec. As no optimum paths are required and specks are immobile, `Ad` messages are transmitted once in the beginning of a simulation run to establish the routes. Table 6.4 summarises the input parameters discussed. Figure 6.10 shows a graphical representation of the neighbourhood and routing links in the specknet of section 6.5.2, configured further with the above input parameters.

About	*Description*	*Value*
Generation:	Transmission rate of `Scouting` messages	5 sec
	Distribution of `Scouting` messages	Uniform $[2, 8]$
Sampling:	Number of error states k	7
	Estimated temperature T_m	last sensor reading
	Limits (for determining e)	$\{1, 2, 5\}$
Integration:	Buffer size s_b	64
	Data lifetime t_b	10 sec
	Confidence threshold r_{Rx}	2 msgs/sec
Action:	Limits (for determining T_{step})	$\{1, 2, 5\}$

TABLE 6.5: Settings for parameters related to the AIS method.

6.5.4 Parameters Related to the AIS Method

In relation to the AIS method, three parameters are examined as independent variables, all related to migration: the path length h_{pl} of sampling `Scouting` messages, and the two types of threshold that can trigger migration of a `Scouting` message during sampling, $v_{msg\_threshold}$ and $v_{speck\_threshold}$. Two sets of experiments are performed, the first to test the ability of integration specks to determine the state of the network presented in section 6.5.4.1, and the second to evaluate the ability of integration specks to affect the environment in section 6.5.4.2.

The remaining of the AIS-related parameters are set by performing trial-and-error simulation runs and are summarised in table 6.5. `Scouting` messages are generated across all sensor specks following the uniform distribution $[2, 8]$ and are transmitted every 5 seconds. To describe their estimated error state e, sensor specks use $k = 7$ different error states with temperature limits $\{1, 2, 5\}$. For example, if a sensor speck estimates that the deviation from its desired temperature is within $|T_d| > 5$ degrees, then its error state is $e = -3$ or $e = 3$ depending on the sign of the difference T_d. Sensor specks use as measurement T_m their most recent temperature reading.

Each integration speck stores received `Scouting` messages in a buffer of size $s_b = 64$ which is refreshed every $t_b = 10$ seconds. Before proceeding with processing

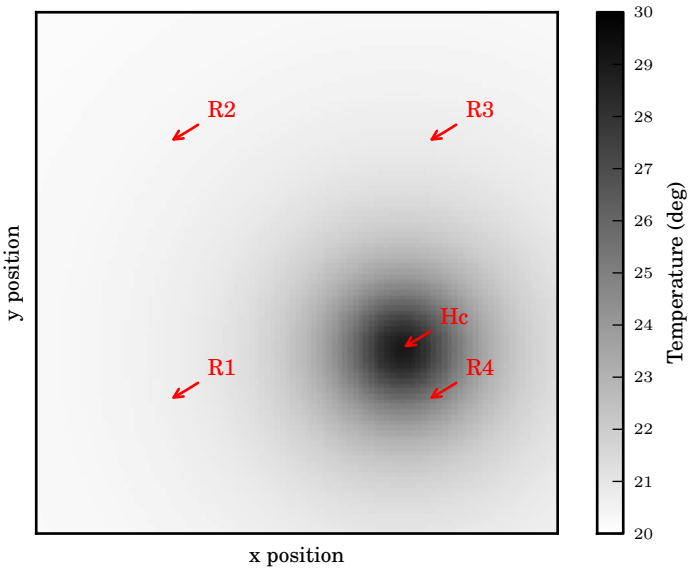


FIGURE 6.11: Temperature map of constant hot spot H_c, $C_{H_c} = \{(t, 9)\}$.

the reported error states, the integration speck checks the reception rate against a confidence threshold of $r_{Rx} = 2$ msgs/sec to assess the quality of incoming data. In case of action, the temperature change T_{step} that an ACU must make is determined by the error state e_{mean} that the nearby integration speck estimates. This error state is transformed to a quantity using the same temperature limits $\{1, 2, 5\}$ as in the estimation of a sensor speck's error state.

With regard to the application problem, the scenario used involves a single hot spot H_c of constant effect: $C_{H_c} = \{(t, 9)\}$. The location of the hot spot is $(0.75, 0.35)$. The effect's scaling vector of both the hot spot and the ACUs is $l = (8, 8, 8)$. The ambient temperature is $T_A = 20$ degrees. Figure 6.11 shows the relevant temperature map and table 6.6 summarises the input values of the temperature model. Additional application scenarios are examined in section 6.5.4.3.

All results, presented in the sections that follow, are produced from one hundred independent simulation runs. The factors randomised in each run are the noise in the sampling of temperature by sensor specks and the choice of neighbour that

Description	*Value*
Ambient temperature T_A	20 degrees
Effect of H_c	$\{(t, 9)\}$
Location of H_c	$(0.75, 0.35)$
Scaling vector l (for H_c and ACUs)	$(8, 8, 8)$

TABLE 6.6: Settings for the temperature model.

Description	*Value*
Path length h_{pl}	$\{2, 7, 11, 16, 20\}$
Migration probability p	1
Trigger at message $v_{msg\_threshold}$	$\{-2, -1, 0, 1, 2\}$
Trigger at speck $v_{speck\_threshold}$	$\{0, 0.1875, 0.375, 0.5625, 0.75\}$
Mean gradient window z	4

TABLE 6.7: Input parameters related to the migration conditions.

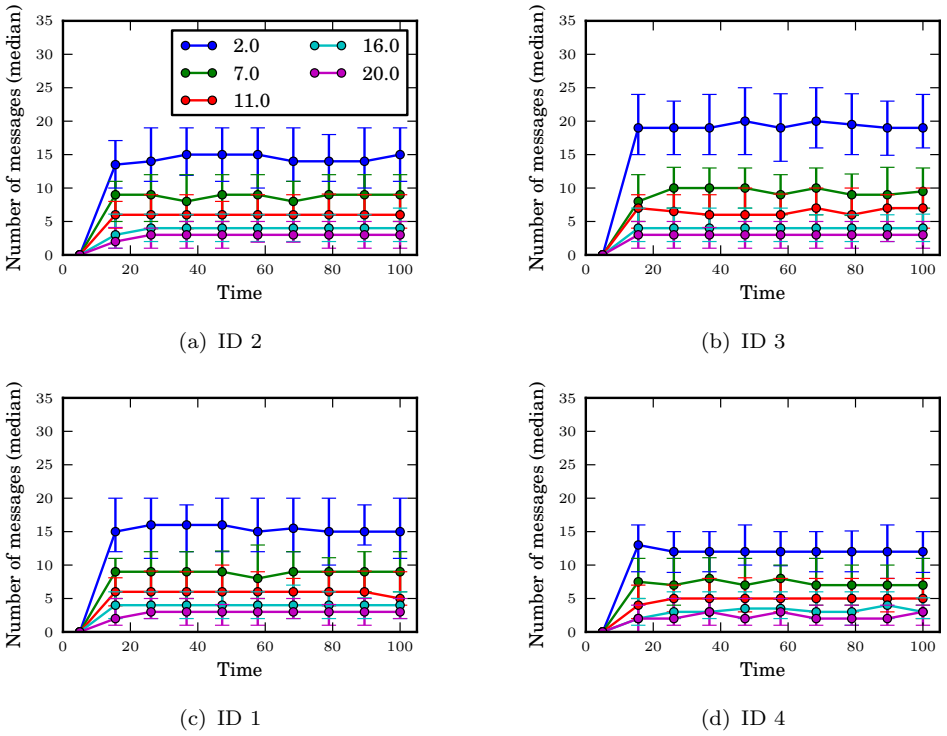
`Scouting` messages are to sample next. Plotted in all graphs is the median with error bars at the 10^{th} and 90^{th} percentiles.

6.5.4.1 Results for Data Collection and Integration

To test the ability of integration specks to determine the state of the network, the reception rate and the mean error of `Scouting` messages at the integration specks are evaluated over time. The reception rate is measured by counting the number of `Scouting` messages stored in the buffer of each integration speck and the mean error is calculated across all samples collected by the stored messages. Each response variable is plotted for each integration speck separately. Response in the network is deactivated.

The values for the independent variables are listed in table 6.7. The three possible triggering conditions considered are:

- the `Scouting` message reaching a range of path length values $h_{pl} = \{2, 7, 11, 16, 20\}$ with migration probability $p = 1$,
- the average of samples in the `Scouting` message exceeding a range of threshold values $v_{msg\_threshold} = \{-2, -1, 0, 1, 2\}$,



(a) ID 2 (b) ID 3

(c) ID 1 (d) ID 4

FIGURE 6.12: Reception rate of `Scouting` messages over time for varying path length h_{pl} at each integration speck.

- the rate of change in the sensor readings of an individual sensor speck sampled by the `Scouting` message exceeding a range of threshold values $v_{speck\_threshold} = \{0, 0.1875, 0.375, 0.5625, 0.75\}$, using a mean gradient window of $z = 4$.

Reception Rate of Scouting Messages Figure 6.12 shows the effect of varying path length on the reception rate. From the figure it is evident that the number of messages received at an integration speck is lower for higher path length. As `Scouting` messages are generated at the same nominal rate by sensor specks, the reception rate would be expected to be the same for all path lengths. However, longer path lengths cause messages to stay present in the network for longer, resulting in higher contention for access to the radio channel and potentially collision or failure to transmit due to exceeding back-off limits of the MAC

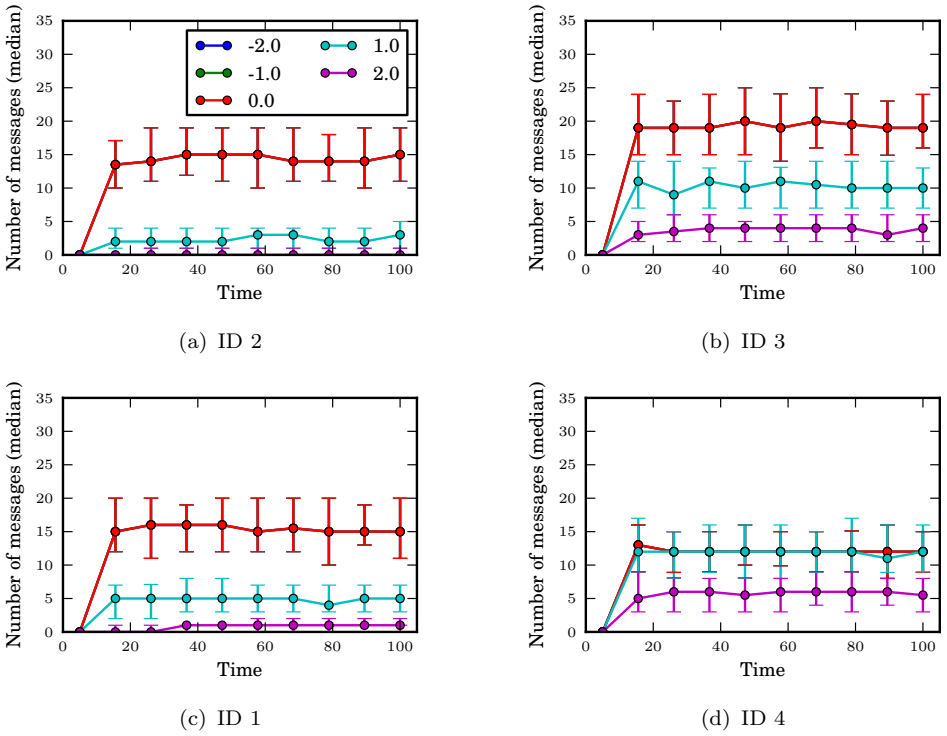


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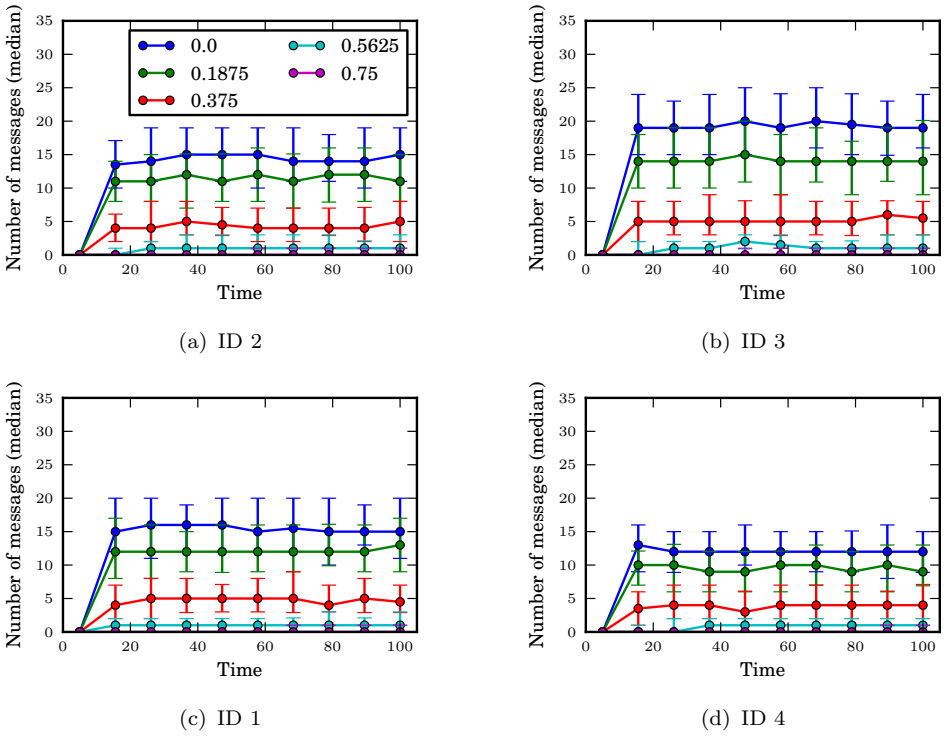
FIGURE 6.13: Reception rate of `Scouting` messages over time for varying values of threshold $v_{msg\_threshold}$ at path length $h_{pl} = 7$ at each integration speck.

protocol. The reception rate is fairly even between integration specks, as the triggering condition is same for all.

Figure 6.13 shows the effect of varying threshold values evaluated at the `Scouting` message for path length $h_{pl} = 7$. This means that if the triggering condition is not met within sampling of 7 sensor specks, then the message is discarded. The figure illustrates that for all integration specks a threshold value of 0 results in a high reception rate. This occurs because any error in the first speck sampled leads to immediate migration. In contrast to the previous triggering mechanism, there is distinct variation between the results of different integration specks. Those nearer the source of temperature disturbance, such as 6.13(b) and 6.13(d), show increased reception rate for values 1.0 and 2.0 as opposed to those integration specks further away from the hot spot. Use of this triggering mechanism is therefore appropriate in providing additional information about local phenomena without increasing the global bandwidth requirements of the network.



(a) ID 2 (b) ID 3

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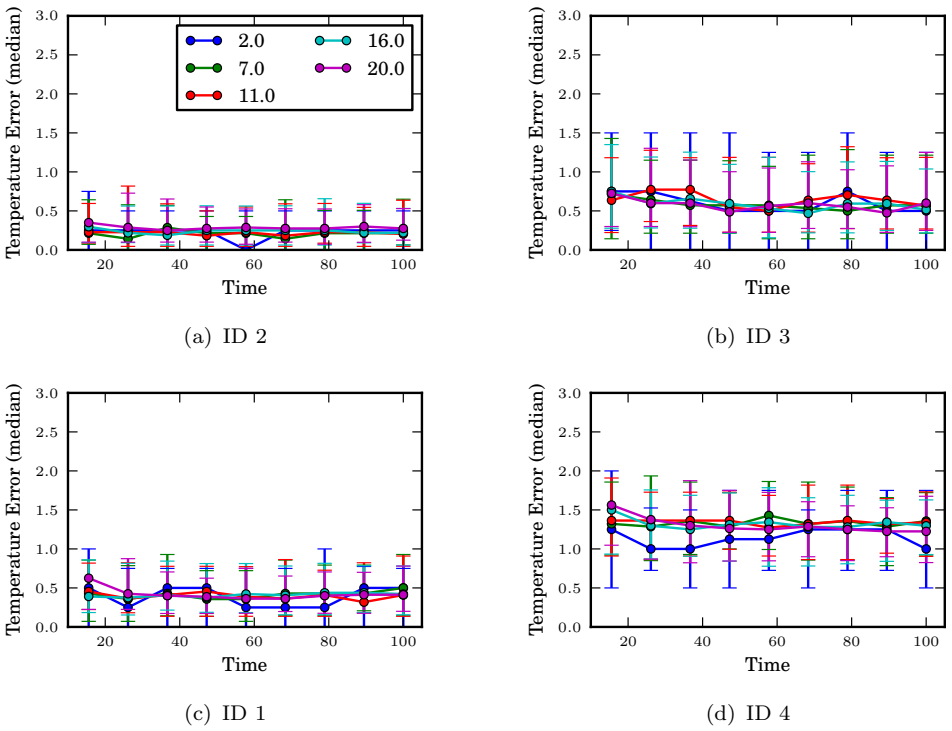
FIGURE 6.14: Reception rate of `Scouting` messages over time for varying values of threshold $v_{speck\_threshold}$ at path length $h_{pl} = 7$ at each integration speck.

Figure 6.14 shows the effect of varying threshold values at the sensor speck for path length $h_{pl} = 7$. As before, if the triggering condition is not met within 7 sensor specks, the message is discarded. This threshold parameter relates to the rate of change of the measured temperature. Since the hot spot has a constant effect upon the environment and no feedback occurs, it might be expected that no `Scouting` messages would migrate. However, as the sensor specks' measurements of the environment are subject to random noise, there is a higher probability of migration for lower threshold values. This can be observed by examination of the graphs. This illustrates an important issue related to implementing systems in reality. As real sensors are always subject to noise, the effect of this noise must be considered in the design of the algorithms.

Mean Error at Integration Speck The results of evaluating the temperature mean error at each integration speck over time are shown for each migration case



(a) ID 2 (b) ID 3

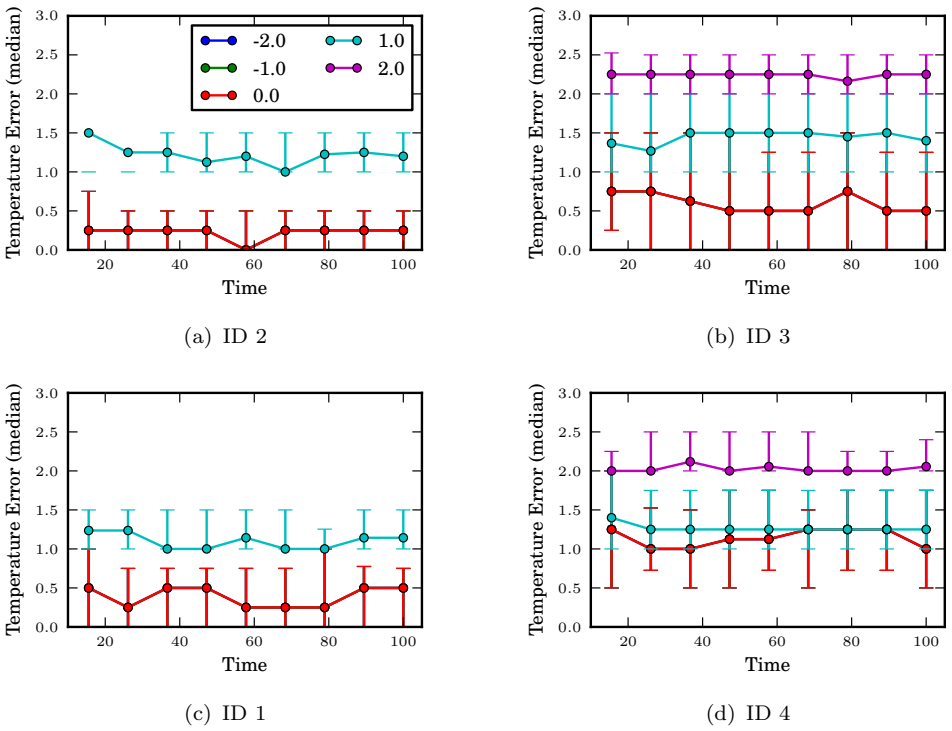
(c) ID 1 (d) ID 4

FIGURE 6.15: Mean error of stored `Scouting` messages over time for varying path length h_{pl} at each integration speck.

in figures 6.15, 6.16 and 6.17. In figure 6.15 little difference is seen between the different path length values. This is to be expected, as samples in all cases come from a representative subset of the sensor speck population.

In contrast, figure 6.16 shows marked variation with the choice of threshold parameter for path length $h_{pl} = 7$. This occurs because only those `Scouting` messages that exceed the threshold migrate to an integration speck. This causes the view of the integration speck to be biased, as can be seen by comparing figure 6.16 to figure 6.15. This bias may cause the integration speck to take action, when this is not truly required. To counteract this, it would be possible to make some of the `Scouting` messages that reach their path-length limit to migrate regardless of whether the triggering condition was met or not. However, this would result in a reduction in the bandwidth saving discussed previously.

In figure 6.17 a delay in the convergence of the mean error at the integration specks is seen for higher threshold values at the sensor speck for path length



(a) ID 2 (b) ID 3

(c) ID 1 (d) ID 4

FIGURE 6.16: Mean error of stored `Scouting` messages over time for varying values of threshold $v_{msg\_threshold}$ at path length $h_{pl} = 7$ at each integration speck.

$h_{pl} = 7$. This is consistent with the results of figure 6.14 where migration of `Scouting` messages is observed to be more likely for lower threshold values. A lower rate of migrating messages impact the number of samples present in the integration specks, and so an adequate history of reported samples takes longer to build up. Between the lower threshold values no significant change is observed in the resulting mean error. This is to be expected, given that the subset of sensor specks sampled remains representative across these input values.

6.5.4.2 Control Performance Results

To evaluate the ability of integration specks to affect the environment, the RMSE of the network is evaluated over time. This global RMSE is calculated from the temperature differences T_d recorded across all sensor specks, alongside the baseline and optimal solution of the examined scenario. In manner similar to the

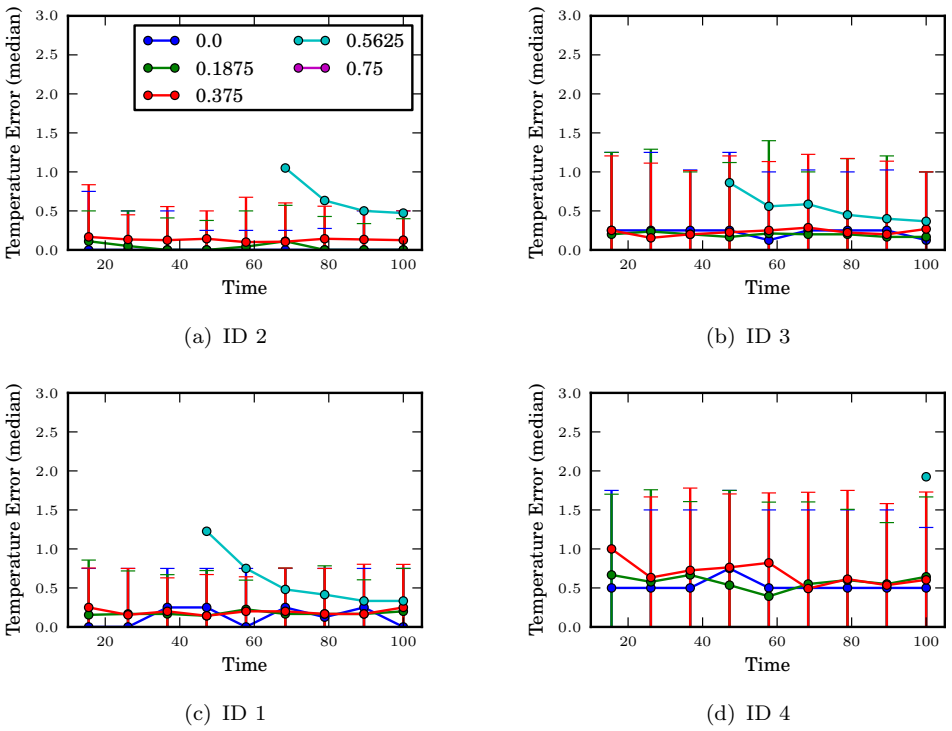


FIGURE 6.17: Mean error of stored `Scouting` messages over time for varying values of threshold $v_{speck\_threshold}$ at path length $h_{pl} = 7$ at each integration speck.

example scenario of section 6.5.1, the baseline is determined by evaluating the state of the network with the ACUs deactivated, while the optimal solution is an approximation obtained using the least squares method. In all other cases, the ACUs are activated and controlled by integration specks. Furthermore, the mean battery level across all sensor specks is plotted over time to examine the energy requirements of the network.

The triggering condition involving a threshold at each sensor speck is not considered, as the rate of change of the temperature is not observable given the sensor noise present. For the other two conditions, related to the path length and the trigger at the `Scouting` message, the input values of table 6.7 are used.

Figure 6.18 shows the global RMSE across all sensor specks in the network over time for varying path length. In all cases the network tends towards a steady state, although it does not achieve the optimal solution. Shorter path lengths result in

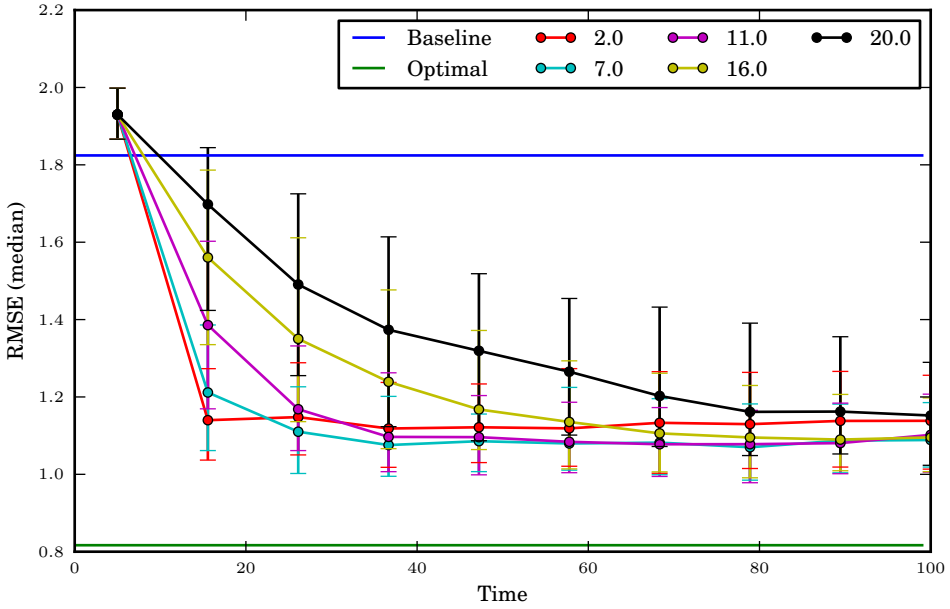


FIGURE 6.18: Global RMSE across all sensor specks over time; no trigger ($p = 1$).

faster convergence. As integration specks only communicate changes to ACUs when they receive new information from `Scouting` messages, the convergence rate of the RMSE is proportional to the reception rate. As shown in figure 6.12, the reception rate decreases with increased path length leading, in turn, to a slower reduction in the RMSE.

Figure 6.19 shows the global RMSE across sensor specks over time for varying threshold at the `Scouting` message and path length $h_{pl} = 7$. In this scenario the positive trigger values result in the system converging. However, the steady state for each parameter is no longer the same. This occurs because of the biased view of the network seen previously in figure 6.16. In this particular demonstration, a trigger value of 1.0 results in the optimal performance, outperforming the values seen in figure 6.18, although it is unlikely this would generalise to other environment configurations or applications.

The energy consumption of the system using the different migration criteria is illustrated in figure 6.20. The energy requirements are practically identical for all

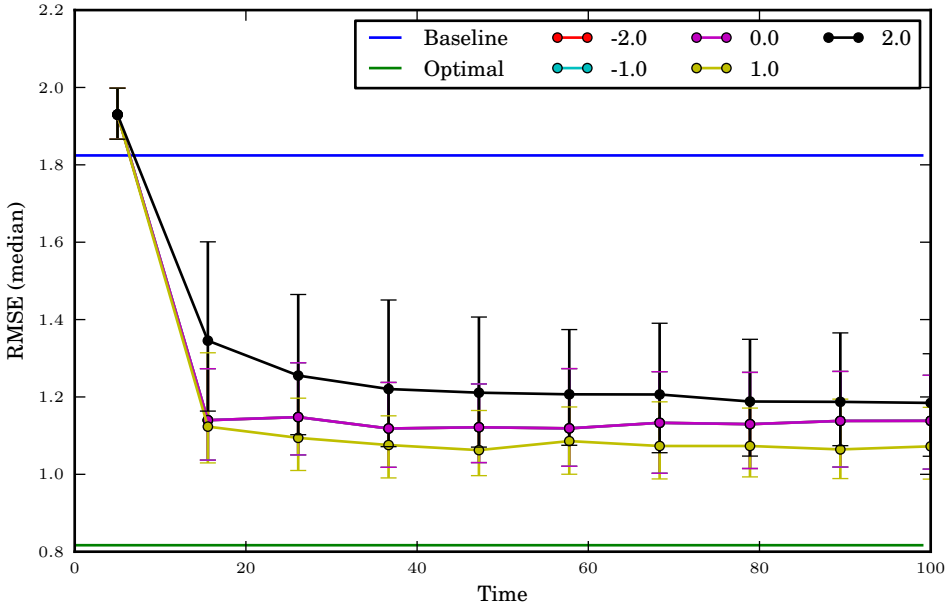
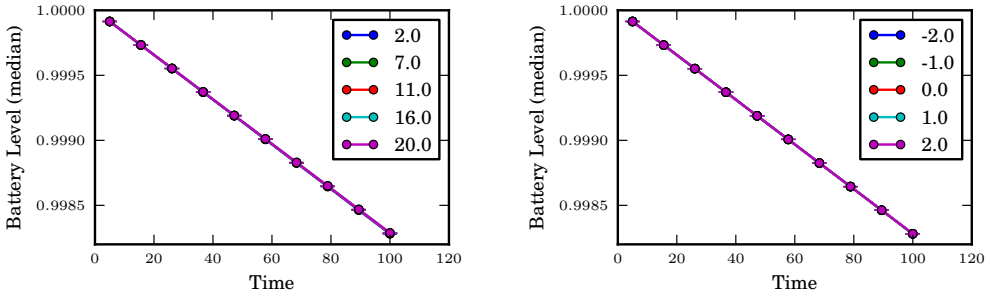


FIGURE 6.19: Global RMSE across all sensor specks over time for path length $h_{pl} = 7$; trigger at message.



(a) No trigger ($p = 1$)

(b) Trigger at message

FIGURE 6.20: Mean battery level across all sensor specks over time.

runs as the power consumption of the specks is dominated by the requirements of the simulated radio hardware, which is active at all times in all scenarios because of the simple CSMA MAC protocol. In order to see any improvements, it would be necessary to select and tune a more efficient MAC protocol to match the communication patterns of the AIS method.

Hot Spot	*Effect*
H_{v_1}:	$\{(0,9),(120,9),(130,14)$
H_{v_2}:	$\{(0,9),(120,9),(121,14),(130,14),(131,9)$

TABLE 6.8: Hot spot details for additional application scenarios.

6.5.4.3 Results for Additional Application Scenarios

To examine the control performance of the system further, the RMSE of the network is evaluated under scenarios where the effect of the hot spot is changed, leaving its scale and location the same. Details about the effect of these hot spots are given in table 6.8. The ambient temperature remains at $T_A = 20$ degrees, the location of the hot spots is $(0.75, 0.35)$, and the scaling factor of the ACUs matches that of the hot spots at $l = (8, 8, 8)$.

Figures 6.21 and 6.22 show the global RMSE across sensor specks over time for varying threshold at the `Scouting` message and path length $h_{pl} = 7$ with different hot spot configurations. In figure 6.21, the effect of the hot spot (H_{v_1}) begins to increase rapidly at t=120 sec by 5 degrees within 10 seconds and remains at this temperature level thereafter. As expected, this causes a sharp deterioration in the RMSE for the baseline and the optimal solution. The response of the system to this change follows a similar trend. The RMSE worsens upon the introduction of the change but it soon settles to a steady state, indicating that the system is capable of detecting unexpected change.

In figure 6.22, the effect of the hot spot (H_{v_2}) is constant except for a momentary increase by 5 degrees at t=120 sec that lasts for 10 seconds. This sudden increase in temperature is registered in the baseline and optimal solution. The results show that the system is also affected by the change, however it is able to recover soon after the change has ended and continues converging to the earlier steady state.

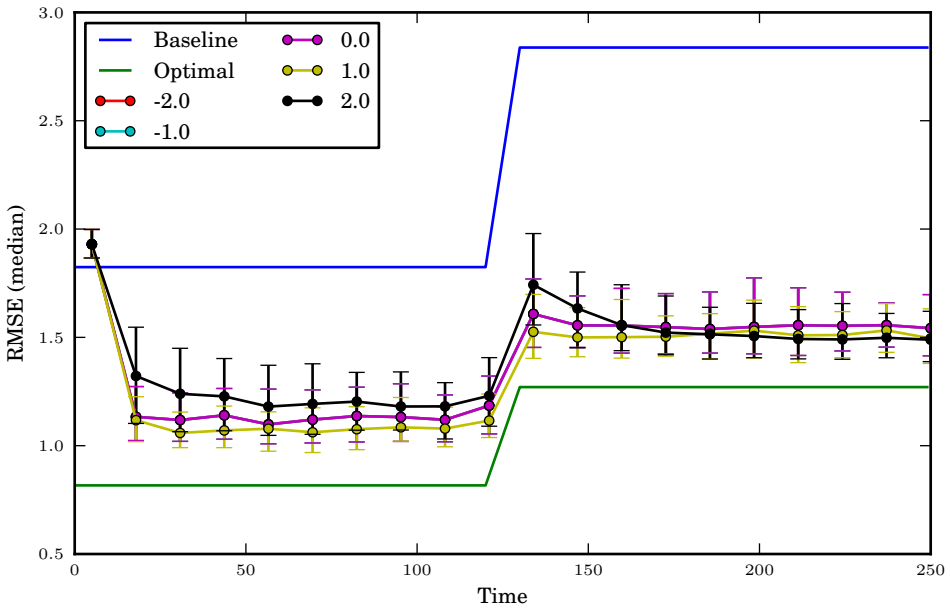


FIGURE 6.21: Global RMSE across all sensor specks over time for path length $h_{pl} = 7$; trigger at message; hot spot of varying effect (H_{v_1}).

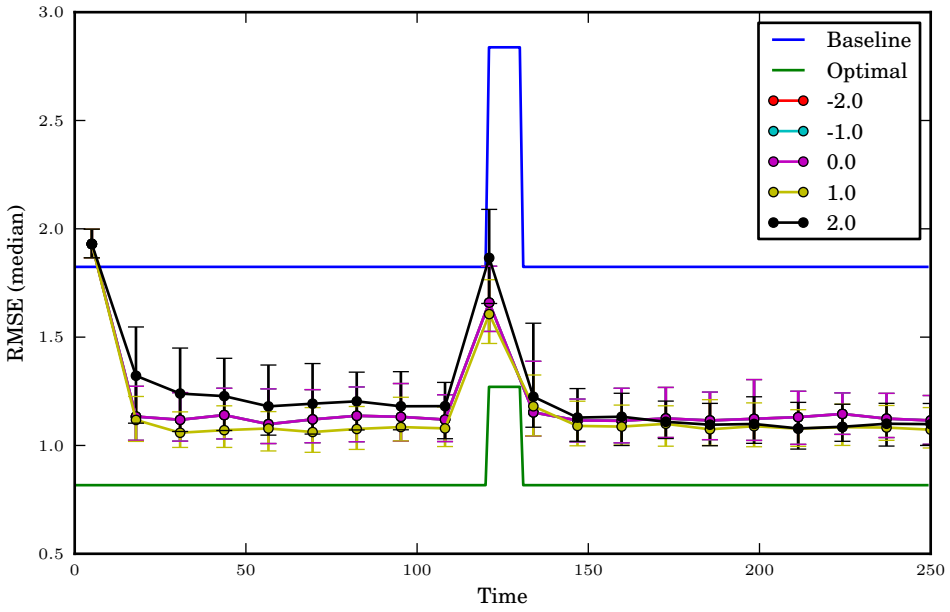


FIGURE 6.22: Global RMSE across all sensor specks over time for path length $h_{pl} = 7$; trigger at message; hot spot of varying effect (H_{v_2}).

6.6 Conclusion

The goal of this chapter was to investigate the process of transferring the model of DC function, obtained in chapter 5, to the specknet. To remind, the greater objective pursued falls under the second research question of this thesis which relates to the idea that consideration of a complex engineered system, such as the specknet, enables development of novel AISs. For this purpose, a simple instance of a problem involving temperature monitoring and control by a representative specknet configuration was examined within a simulation environment.

The approach followed consists of mapping the identified immunological elements onto the specknet, implementing the AIS method in development in a simulated specknet, and applying the method to a problem of monitoring and control of temperature. The process of mapping the DC model onto the specknet, presented in section 6.3.1, involved an abstract version of the engineered system. This in conjunction with focussing on the role of data sampling and reporting, again at a level of minimal engineering detail, allowed to examine how the elements of the AIS in development can be of service in an engineered context.

The work on implementation, presented in section 6.3.2, involved a more concrete version of the specknet. This required part of the focus to be placed on the lower layers of the engineered system and their associated constraints which were specific to the engineering aspect of the system and irrelevant to the AIS method. Testing the AIS method, presented in sections 6.4 and 6.5, involved examining a typical application problem for the specknet. As such, the metrics used for evaluating the performance of the system were related more to the specific problem domain and less to those aspects of the system linked with the AIS method.

Throughout this approach the level at which the engineered system is treated changes. Initially, the specknet is considered in the abstract, bearing only the key characteristics and requirements that a generic wireless sensor network has. However, as the process progresses, the specknet becomes a predefined concrete,

albeit simulated, networking system, requiring detailed specification and setup. This change causes the specifics of the engineered system to overshadow the immunological aspect of the AIS investigation. This is particularly illustrated in the parameters section 6.3.3, where the research problem partly becomes an application-to-engineering problem due to implications arising from having to define the underlying system.

It is concluded, thus, that having a concept of an engineered system can be helpful for developing novel AIS. However, the more concretely the engineered system is treated, at least during the initial stages of AIS development, the more likely it is for the research to be driven away from the immunological aspects and drawn into an engineering frame of working about the problem. By following this approach, novelty in terms of the mechanisms that the AIS exploits from the immune system is ultimately less likely to be immunologically driven and more likely addressed from an engineering perspective.

Chapter 7

Analysis and Conclusions

7.1 Thesis Summary

This thesis set out to investigate the idea of whether an engineered system, such as a wireless sensor network, enables computational exploration of the immune system in directions novel for the field of AISs.

Chapter 2 overviewed the immune system from a computational and networked perspective, reviewed a number of dominant immunological theories examining their impact on the field of AIS, and critiqued the approach of the AIS community to immunological inspiration. Thereafter, the current literature on the combined subjects of AISs and WSNs was reviewed, followed by a discussion on methodologies for AIS development as found in the literature. The chapter concluded with identifying agent-based modelling as a suitable technique for use as part of the investigation in this thesis.

Chapter 3 introduced the domain of WSNs with a focus on specknets. The research challenges of such engineered systems were discussed in relation to their networking characteristics and system requirements. Furthermore, a map for researching and a framework for studying specknets were proposed. The chapter

ended by briefly explaining the concept of a number of networking services which were used later on in the thesis.

Chapter 4 started with introducing the methodology followed for carrying out the research in this thesis. The results of the first step regarding a study in how the specknet and the immune system correlate were presented first. Then, the theoretical context of the research was defined, identifying Cohen's cognitive paradigm as appropriate for further exploration. The cognitive immune system was examined in more detail and studied alongside the specknet. In the end, the immune focus of the thesis was established at the theoretical and biological levels, choosing co-respondence and the dendritic cell respectively.

Chapter 5 focussed entirely on the dendritic cell. The first part of the chapter studied the immunological literature in order to gain an understanding in the behaviour of DCs. As such, a number of DC aspects were examined, including their development, distribution and the dominant immunological models about their role with a focus on migratory activity. The second part of the chapter dealt with the development of an ABM which attempted to capture key aspects from the life cycle of immunogenic DCs. The chapter finished with a discussion that reflected on the use of DCs in AISs.

Chapter 6 investigated the process of developing a novel AIS by directly including the specknet in the process. The process started with examining mapping options between the model of DC function from the previous chapter to the specknet environment. The resulting AIS method was implemented in simulation, and applied to a temperature monitoring and control problem. The chapter ended with assessing the extent to which the approach followed facilitated exploration of novel AISs.

This chapter revisits the relationship between the cognitive immune system and the specknet, and presents an analysis concerning the structural organisation, communication and input aspects in section 7.2. Thereafter, in section 7.3 the

research questions of this thesis are evaluated, leading to the proposal of a principled methodology for the field of AISs based on the experience and findings of the work presented in this thesis. The chapter concludes with directions for future work in section 7.4.

7.2 Analysis

7.2.1 Structural Organisation

Immune system

In the CIS co-respondence is characterised as the central processing unit of immune function, see section 4.4.1. From the point of immune anatomy, the central processing unit is distributed throughout the body and found in lymph nodes which, in the context of the CIS, are regarded as "local, ad hoc brains" [27, p. 162]. Lymph nodes are the place where immune cells gather to present their findings from the tissues and engage in intensive exchange of information, what Cohen calls co-response signals. This processing eventually results in a joint immune decision, which is carried out by immune agents that exit lymph nodes and return to tissues in order to take action. When considering co-respondence, thus, at least two anatomical spaces are deemed important for the organisation of the immune system, the tissues and the lymph nodes.

Specknet

As explained in section 3.3.4, the main application-end role of specknets is to sense and process data from the environment and, if necessary, proceed to appropriate action. The basic system setup of classic WSNs incorporates two types of nodes, sources and sinks, see section 3.2.2. Sources capture data from a sensor field and report their readings to sinks, which are responsible for processing the incoming

data. In specknets, this structure is augmented by the inclusion of actuators in the system. Moreover, sinks are considered part of the local network of sources and to some extent equivalent to a device that performs sensing, as opposed to the concept of a single, distant base station that is outside the sensor field typically met in WSNs.

Comparison

In the specknet, an engineered system that may consist of potentially numerous individual units, deployment of sources and sinks to sites of interest is most likely to be performed at random, or manual placement of specks may be chosen in cases where it is critical for certain areas to be covered by sinks. In the immune system, however, the position of lymph nodes is far from random, as discussed previously in section 5.3.2. Furthermore, the specknet may be dynamic, that is specks may be mobile, whereas in the immune system the spatial relation between bodily tissues and lymph nodes is immutable.

7.2.2 Communication

Immune system

In the immune system, communication is chemical-based. One way to approach the subject is by distinguishing two different scales, the molecular and the cellular. At the molecular scale, immune communication is mediated by cytokines which enable mainly local interactions, but can also permit more distant communication links [72, p. 347]. Immune cells rely heavily on molecular signalling for interacting with each other and with other body cells. Interactions where cytokines may be found on the membrane of the interacting cells delivering messages upon direct contact, or in soluble form communicating information to cells in close proximity, are examples of local communication. An example of longer range communication

is when cytokines released by certain types of effector lymphocytes stimulate undifferentiated bone marrow cells to turn into effector leukocytes, which are important for taking action at a site of infection. This can be seen as a case of one-way communication link, in which molecular messages for recruitment of more leukocytes to a site of emergency reach the production line of immune cells.

In a more abstract sense, immune communication exists at the cellular scale between different anatomical spaces, where it is mediated by the different classes of immune cells. For example, in the underlying immunological events of the ABM of chapter 5, the migration of activated dendritic cells and effector T cells could be seen as communication links between peripheral tissues and lymph nodes, where information about an infectious incident and a corresponding response is exchanged between the involved locations. Recirculation of naive lymphocytes between blood and lymph—the fluid that flows in lymphatics—[72, p. 10] is another example of cell-mediated immune communication. As they flow within the circulatory system of blood and lymph vessels, naive lymphocytes go through peripheral lymphoid organs. Since it is not possible for each lymphoid organ to accommodate all existing somatic receptors carried by naive lymphocytes at all times, the latter are continually exchanged from one lymphoid organ to another, so that in case of infection anywhere within the body matching naive lymphocytes are arrested upon arrival at nearby lymph nodes.

Specknet

In specknets, communication is designed to be predominantly radio-based, as is the case for the majority of WSNs. Being omnidirectional, a radio transmission from a source speck travels in all directions, but it has finite range which is proportional to the energy used for the transmission to happen. This means that, generally, for two specks to be able to communicate directly, their radio ranges must overlap. However, because radio is a shared communication medium, mechanisms are required to control access of specks to radio channels. For this

reason, medium access control (MAC) protocols have been developed to provide efficient and fair co-ordination of wireless network communication. In terms of the research map of figure 3.5, the subject of communication is tightly related with the data link layer, whereas issues regarding low-level implementation aspects, such as hardware design, are considered part of the physical layer. MAC protocols are usually seen as sitting between these two layers.

Physically, the communication graph of a specknet is defined by the constraints of the radio components of specks, their actual locations, that is, the distances between them, and the environment in which they are situated, for instance whether there are any obstacles present. With the use of a MAC protocol, this 'physical' communication graph may be further cut down, allowing only a subset of the physically available links to become connected. Various MAC schemes exist for this purpose. According to the literature [5], [76, p. 114–119], the basic categories are: *contention-based* protocols, which contain a random element for providing access and operate in a fully distributed manner; *fixed assignment* protocols, which offer pre-determined, fixed allocation of the medium based on, for example, time or frequency division, and typically require a controller to synchronise the nodes of the network and allocate the slots; *demand-based* protocols, which also provide exclusive allocation of resources to nodes but only for a short term, and can be implemented in a central or distributed way.

Comparison

Perhaps the most critical aspect where the relationship between the immune system and the specknet diverges is communication. Specknets have specific engineering requirements, among which energy conservation is of vital importance. As explained in sections 3.2.1 and 3.3.3, radio usage is a power-hungry activity for a battery-supported speck. The further a speck attempts to transmit a message, the more energy it requires. This case is aggravated by energy waste due to problems related to MAC operation, such as the possibility of transmission collisions,

idle listening or overhearing messages destined to others [40], [76, p. 119–120]. In the immune system, on the other hand, communication can be regarded as nearly free, in that the impact of its cost to the system is trivial compared to the case of specknets. Immune communication can be considered cheap, because it is supported by mechanisms involving constituent elements of the system, namely cytokines and immune cells. Indeed, they come at the price of requiring continual renewal, but this need is fulfilled by the surrounding bodily infrastructure.

In terms of managing communication, a specknet relies on controlling algorithms and protocols, which are dependent to some extent to changes occurring in the physical layout of the network. As discussed in section 3.4.1, the topology of a specknet is susceptible to frequent changes, due to mobility of specks, deployment of new units or failure of existing ones. MAC protocols, thus, need to incorporate mechanisms that deal with such events that disrupt connectivity by causing the underlying communication graph to become disarranged. However, in immune communication, events such as mobility or recycling of immune agents are the very mechanisms that are being exploited by the system in order to exchange important information between cells or deliver messages to different anatomical sections, see sections 2.2.2 and 4.2.

7.2.3 System Input

Immune system

At an abstract level, the input received by the CIS is the multitude of the different conditions that constitute the state of the body, referred to as immunogenic tissue states, see section 4.3.3. For example, tissue which is afflicted by injury or wound releases molecular signals, indicating the state of the site has changed from healthy to damaged. These state-related signals are fed into the CIS and are transformed into appropriate response states with the help of the immune central processing unit, co-respondence.

At a lower scale, the input to the immune system comes in form of molecular shape [28]. Molecular shape is captured by two types of immune sensors, the innate receptors and the antigen receptors. The former are shared across all types of immune cells, whereas the latter are available exclusively to lymphocytes.[1] Innate receptors are encoded from genes inherited through the germ line and capture non-specific input. The source of this input varies from body-generated signals, for example cytokines produced from tissue or other immune cells, to signals derived from pathogens.

The case of antigen receptors is somewhat more complicated. Antigen receptors are of higher specificity, which suggests that they are able to capture input potentially more informative for the system than innate receptors can. Furthermore, antigen receptors are being manufactured by lymphocytes themselves, either randomly or under selective pressure, and are unique to each lymphocyte. Their creation is not driven by inherited genes [27, p. 143], which means different immune systems develop over the course of their lifetime a set of antigen receptors that is characteristic to their individual history. Given the fact that the set of lymphocytes, and subsequently that of antigen receptors, is variable, individual antigen receptors are not *all* necessarily essential to the immune system, even if in concept they provide highly precise sensors.

Specknet

Capturing input from the environment is the central to the specknet functionality. A wide range of sensors can be used to translate physical phenomena to analog or digital signals. The main category of sensors considered within the general WSN literature is passive and omni-directional [76, p. 31]. The type of sensors incorporated to a network is determined by the application layer. Depending on the environmental parameters of interest, sensor requirements may vary from light, humidity or pressure to chemically sensitive sensors. Each speck can be

[1] They can also be found on their own, in soluble form when released from lymphocytes.

equipped with more than one sensor, since the amount of power they consume is generally negligible compared to other components, such as transceivers [107]. Sensor readings typically suffer from unwanted variations. Examples of deviations in sensor measurements include noise, bias and scale. Noise is a random fluctuation varying over time added to the captured signal due to various environmental sources, however it can be treated as a gaussian approximation of zero mean and therefore cancelled. Bias and scale errors are found in linear sensors, and are usually corrected by applying some form of calibration.

Comparison

Both the immune system and the specknet rely on similar mechanisms of distributed sensing to capture system input. The immune system is not selective with respect to the source generating the incoming information. Immune receptors will accept any molecular shape that matches them, although the ensuing reaction at the scale of cells is incredibly difficult to trace out due to the large number of factors involved, such as the concentration of the input signal, the state of the cell at the moment of reception, the presence of additional signals in the environment. In the specknet, sensing is limited to certain environmental factors by the supported sensory equipment, while the response at the level of specks can be designed to be as simple or as complex as dictated by the engineering solution.

However, when examining specknets from an AIS perspective, the concept of system input need not be restricted to sources that are external to the system. In manner similar to the CIS accepting data related to the state of the body, an immune-inspired approach to the specknet may consider as input data concerning technical aspects of the network, instead of or in addition to data about the application layer drawn from the environment, see figure 4.5. In fact, a first example that illustrates this idea can be found in the AIS literature on ad hoc wireless networks. Recent work by Drozda et al. [46] adopts a cross-layered approach where a number of energy-sensitive features related to the MAC protocol,

routing and transport layers are combined to describe the operational state of the network for use in a misbehaviour detection system, based on the immunological concept of co-stimulation; preceding work by this research group is reviewed in section 2.4.

7.3 Evaluation of Research Questions

This section revisits the research questions set at the beginning in chapter 1, and answers them in the light of the evidence provided by the work presented throughout this thesis. In addition, it discusses the findings in relation to the existing body of AIS literature.

7.3.1 Question 1

> How far can one push the immune metaphor within the environment of a wireless sensor network, so as to achieve both exploitation of novel immune properties and develop solutions that meet the requirements of the engineered system?

The first research question essentially asks whether the field of AISs has the potential to develop novel immune-inspired solutions that can be of benefit to WSNs. From the study in the analogies between the specknet and the immune system presented in sections 4.2 and 4.3.4, it is evident that a wireless sensor network provides several *mapping points* that match well a variety of immunological characteristics. The potential of such research direction is highlighted, in particular, by the many questions raised in section 4.2.2 about the challenges of specknets. Immune properties such as self-organisation, scalability, resiliency, adaptation and maintainability are close to *key requirements* of WSNs. Therefore, AIS that encapsulate like properties can be of service to meet challenging WSN requirements.

The work presented in chapter 5 where a model of DC functionality was derived from studying immunology and the subsequent attempt to transfer this model in the specknet environment in chapter 6, showed that inevitably the metaphor needs to be adapted to meet the engineering constraints of the application. For example, in the ABM migration of DCs is assisted by the presence of gradients that tightly surround a lymph-node location, whereas in the specknet migration of `Scouting` messages relies on a networking service provided by the WSN literature. Although the resulting implementation is not biologically faithful in a mechanistic sense, it still captures essential functionality of the immune system.

Moreover, the implementation of chapter 6 shows that it is possible to transfer certain aspects from the adapted DC model to the complex engineered system. Specifically, it was shown that the method of collecting samples from the tissue environment to a lymph-node location, achieved by dendritic cells in the immune system, could be replicated in the specknet by use of radio messages. Experiments showed that it is possible to build a picture of the state of the local environment through by collecting and then integrating this data. The method is consistent with the engineering constraints of the specknet and provides a promising basis from which to undertake future work focussed directly on the engineered system.

7.3.2 Question 2

> To what extent does a complex engineered system such as a wireless sensor network offer a suitable platform for developing algorithms which exploit novel computational features of the immune system?

Having accepted that the field of AISs can provide solutions useful for WSNs, the next research question asks whether consideration of a complex engineered system enables exploitation of novel immune aspects for AIS development. Indeed, a suitably rich engineering environment, such as a specknet, provides opportunity to exploit rich computational properties of the immune system, so long as there are considerable mapping points between the two.

This thesis shows that a novel immune property, that of *mobility* of DCs, has been exploited, which differentiates this work from previous research on the DC in the AIS literature. The examined application domain of WSNs provides a natural platform in which to exploit this property. The mobile feature of DCs leads to possible exploitation of other immune properties which are novel from an AIS perspective, such as *migration*. Furthermore, the specknet platform provides chance for examining more typical properties, such as data filtering and classification [54].

Chapter 6 gives evidence through the experimental results that this is a promising avenue of work, albeit still in its infancy. For instance, the simple AIS implemented in the monitoring application problem is able to detect temperature variations under different migration conditions.

7.3.3 Question 3

> Can a principled methodology be developed which enables blending of ideas derived from two complex systems, a biological one and an engineered one, and if so, what stages would it involve?

The final research question refers to the idea of a principled methodology which would provide a link between complex systems from biology and engineering, and would allow blending of ideas originating in both sides—in the case of this thesis, the systems explored are the immune system and the specknet in the context of the AIS field. Based on findings from this thesis, the following steps are proposed as an answer:

1. Study correlation at systems level between the biological and the engineered systems.
2. Define study framework for the engineered system.
3. Choose theoretical context for the biological system, using findings from step 1.

4. Choose theoretical focus for the biological system, considering framework from step 2.
5. Choose focus at the biological level, considering framework from step 2 and decision from previous step.
6. Model biological elements of interest.
7. Formulate bio-inspired algorithm, method or protocol, founded on model from previous step and considering framework from step 2.
8. Examine mapping options between resulting bio-inspired tool and engineered system.
9. Investigate implementation of bio-inspired tool in engineered system.
10. Apply implementation from previous step to specific problem.

In order to instantiate the proposed methodology for AISs, the *role* of the AIS practitioner and the engineer must be defined first:

AIS practitioner: seeks to understand the immune system in an abstract computational manner with the aim of applying this knowledge to a variety of problems.

Engineer: designs and implements systems to solve practical problems.

It should be clarified that the definition with respect to the AIS practitioner is the author's suggestion for the role that a researcher interested in the field of AISs should assume. This definition is not necessarily in line with current practice where the intention is heavily focussed on developing applied artificial immune systems (AAISs).

A further clarification concerning what components are viewed by the author as integral to the field of AIS is illustrated in figure 7.1. The ideal goal for the field of AIS is to showcase an array of competent computational tools that encapsulate the multiple facets of immune functionality and are available for use

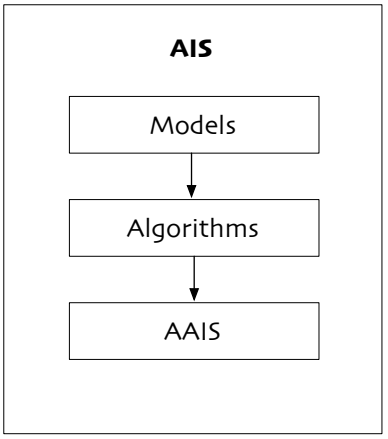


FIGURE 7.1: Component parts integral to the field of AISs.

to the computational scientist or engineer; let these be represented by the *algorithms* component in figure 7.1. Such algorithms stem from the knowledge gained through the systematic modelling of the immune system by AIS practitioners. This knowledge is distilled into a library of *models* shared among the AIS community. At the other end, through *AAISs* the algorithms are employed to address real-world problems within computing and engineering.

Considering the component parts of AISs, it is suggested that the models component relates to the first six steps of the proposed methodology, the algorithms component links with step seven and the AAIS component with the last three steps. Additionally, given the aforementioned role definitions, it is suggested that the first eight steps of the proposed methodology are of concern to the AIS practitioner, whereas the last two steps involve primarily the engineer. These suggestions are explained and collated with the main methodological approaches to AIS development below.

On the subject of AIS methodologies Andrews [7, p. 192] argues:

> An alternative approach [to the development of a novel AIS] would be to bias the route through the CFA [conceptual framework approach] by having either an application or type of algorithm you wish to develop in mind before you start.

in response to the lack of a problem-oriented perspective in the conceptual framework by [122, 123], discussed in section 2.5.1. By definition, the proposed methodology depends on the direction provided by the nature and characteristics of the engineered system for probing the immune system. For instance, in the case of this thesis, examining the networking character of specknets and outlining the study framework for specknets in chapter 3 were essential in narrowing investigation down to the CIS and the DC in chapter 4. As such, the author concurs with Andrews' position, provided that an *abstract system* or a *class of application problems* is selected to aid throughout the AIS development process, instead of involving a concrete system or a predefined application problem given the conclusions reached in chapter 6.

In this regard, the proposed methodology calls for a clear distinction between development of immune-inspired algorithms and their implementation to the engineered system. During the development process the AIS practitioner need not be concerned with implementation details. Otherwise, the specifics of applying AIS to the particular system or problem can overshadow and even sidetrack the investigation. For example, in chapter 6 implementing the aspect of mobility in SpeckSim raises issues which are both irrelevant to the immune-inspired behaviour of the `Scouting` message and require domain-specific knowledge to be resolved, such as identification of specks, neighbourhood creation and looping prevention.

The eighth step of mapping in the proposed methodology is pivotal for determining effective applicability of the developed AIS algorithms to the engineered system. For informed decisions to be made, however, knowledge on technical aspects of the engineered system is required; knowledge that is tailored to the needs of the AIS practitioner. This is where immuno-engineering can help facilitate the transition from the abstract concept to the specifics of the engineered system. According to [129]:

> Immune-engineering takes into account the differences between artificial systems and biological systems: for example, the different numbers, kinds, and rates of signals that need to be monitored and processed; the different kinds of decisions that need to be made; the different effectors available to support and implement those decisions; and the different constraints of embodiment, either physically or virtually engineered.

As such, immuno-engineering can contribute to the proposed methodology by acting as the middleman between the AIS practitioner and the engineer, facilitating the process of adapting the AIS algorithm to the needs of the engineer.

To benefit from the proposed methodology in the long run, the AIS community needs to build up and share a core library of immunological models for internal use. Modelling is identified as a fundamental process in both the conceptual framework and immuno-engineering. However, in neither of these approaches is a model explicitly recognised as an output of the process. It is argued that by maintaining such library AIS practitioners will spend less effort in trying to reinvent the wheel with every modelling attempt and new models of unexplored immunological aspects will be less likely to turn out overly simplistic.

Furthermore, once a set of immunobiological models is established, extensions describing various theoretical interpretations can be developed to explore ideas coming from theoretical immunology. To enable progress in this direction, the AIS field would benefit from adopting a dialectical scheme, such as the one proposed in figure 2.4. It is suggested that such move will lead the AIS field to develop a commonly accepted language—not necessarily matching immunological parlance—that is used consistently within the community. This will enable AIS practitioners to effectively communicate and exchange research ideas, instead of being a group of isolated islands of work.

7.3.4 Summary

To summarise, this section answers the research questions of chapter 1, supported by evidence provided by the work presented in this thesis. It is concluded that the field of AISs has the potential to develop immune-inspired solutions useful for WSNs, and that inclusion of a suitably rich engineered system, such as WSNs, in the AIS development process enables novel aspects of the immune system to be exploited.

In 7.3.3, a principled methodology is proposed which aims at allowing blending of ideas between two complex systems that come from biology and engineering. The proposed methodology is instantiated for AISs and collated with the conceptual framework [122, 123] and immuno-engineering [129]. Both approaches are deemed to contribute vital directions for successfully following the steps of the proposed methodology within AISs.

7.4 Future Work

Future work can be addressed in a number of angles:

- In terms of immunological probing, Cohen's concept co-respondence, see section 4.4.1, offers a powerful immune framework for the AIS field to continue probing the immune system in a more coherent manner. A first small step towards exploring the concept of co-respondence is made in this thesis with the study of the DC functionality. Any of the involved immune agents is a potential avenue to explore for the first time or afresh, at the basis of individuals or at an interconnected level.
- In terms of WSNs, they offer a promising platform in form of an abstract system to use in AIS development, while the concrete version, simulated or real, can play the role of a case study system in the context of immuno-engineering. In addition, the case study of temperature monitoring and

control presented in chapter 6 provides a starting point for developing and potentially deploying a fully functioning WSN, based on principled development of algorithms informed by immunology.

- Finally, in terms of AIS, the methodology proposed in section 7.3.3 should be evaluated. Steps to be taken towards this direction include suggesting and agreeing on practical ways to enhance communication within the AIS community, and establishing the grounds for developing a common library of fundamental immunological models for use by AIS practitioners.

The distinct *role* that the field of AISs needs to embrace is to truly understand the immune system by developing its own set of models, not useful to immunology or to engineers, but useful for internal consumption; so that the field has a *core* to work with in order to contribute computational tools to the engineer and potentially feedback to immunology.

Appendix A

Publications

Below are listed the publications that resulted from this thesis. A set of symbols are used to denote the amount of contribution in each publication:

{> major contribution, = equal contribution, < minor contribution}

> D. Davoudani, E. Hart, and B. Paechter. An immune-inspired approach to speckled computing. In *Proc. of the 6th International Conference on Artificial Immune Systems (ICARIS)*, volume 4628 of *LNCS*, pages 288–299. Springer, 2007

< E. Hart, D. Davoudani, and C. McEwan. Immunological inspiration for building a new generation of autonomic systems. In *Proc. of the 1st International Conference on Autonomic Computing and Communication Systems*, pages 1–10. ICST, 2007

> D. Davoudani and E. Hart. Computing the State of Specknets: An Immune-Inspired Approach. In *Proc. of the International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS)*, pages 52–59. IEEE, 2008

> D. Davoudani, E. Hart, and B. Paechter. Computing the state of specknets: Further analysis of an immune-inspired model. In *Proc. of the 7th International Conference on Artificial Immune Systems (ICARIS)*, volume 5132 of *LNCS*, pages 95–106. Springer, 2008

= E. Hart and D. Davoudani. Dendritic Cell Trafficking: From Immunology to Engineering. In *Proc. of the 8th International Conference on Artificial Immune Systems (ICARIS)*, volume 5666 of *LNCS*, pages 11–13. Springer, 2009

< E. Hart, C. McEwan, and D. Davoudani. *Exploiting collaborations in the immune system: the future of Artificial Immune Systems*, pages 527–558. Springer-Verlag, 2009

= E. Hart and D. Davoudani. An engineering-informed modelling approach to AIS. In *Proc. of the 10th International Conference on Artificial Immune Systems (ICARIS)*, volume 6825 of *LNCS*, pages 240–253. Springer, 2011

Appendix B

Simulation Model: NetLogo Code

Below is listed the code for the ABM of chapter 5.

```
breed [lymph-nodes lymph-node]
breed [infection-sites infection-site]
breed [dendritic-cells d-cell]
breed [effector-t-cells t-cell]

patches-own [
  lymph-chemical
  infection-chemical
  sampled
]

infection-sites-own [infectious-signal]

dendritic-cells-own [
  lifespan
  sampled-infectious-signal
  reporting
]

effector-t-cells-own [lifespan]

to setup
  ca
  ask patches [ set pcolor white ]
  if fix-seed? [ random-seed input-seed ]
```

```
  setup-lymph-node lymph-node-count
  setup-infection infection-count
  update-gradients
  setup-dendritic-cells d-cell-count

  do-plots
end

to setup-lymph-node [num]  ;; Set up lymph nodes at random locations
  create-lymph-nodes num [
    setxy random-pxcor random-pycor
    set color orange
    set shape "x"
  ]
end

to setup-infection [num]  ;; Set up infection at random locations
  create-infection-sites num [
    setxy random-pxcor random-pycor
    set color red
    set shape "bug"
    set infectious-signal infectious-level
  ]
end

to setup-dendritic-cells [num]  ;; Set up creation of dendritic cells
  create-dendritic-cells num [
    setxy random-xcor random-ycor
    set color green
    set lifespan random-normal mean-d-cell-lifespan std-d-cell-lifespan
    set reporting false
  ]
end

to go
  diffuse lymph-chemical lymph-diffusion-rate
  diffuse infection-chemical infection-diffusion-rate
  update-gradients
  sample-tissue
  move-dendritic-cells
  setup-effector-t-cells
  check-d-cell-death
  move-effector-t-cells
  check-effector-t-cell-death
  clear-infection
```

```
  check-infection-site-death
  tick
  do-plots
end

to update-gradients
  ask lymph-nodes [
    set lymph-chemical (lymph-chemical + lymph-release-rate)
  ]
  ask infection-sites[
    set infection-chemical (infection-chemical + infection-release-rate)
  ]

  ask patches [
    set lymph-chemical (lymph-chemical * (1 - lymph-decay-rate))
    set infection-chemical (infection-chemical * (1 - infection-decay-rate))

    ifelse (lymph-chemical > 0.01 and infection-chemical > 0.01)
      [ set pcolor scale-color gray ((lymph-chemical + infection-chemical) / 2) 10 0 ]
      [ if lymph-chemical > 0.01
          [ set pcolor (scale-color blue lymph-chemical 10 0) ]
        if infection-chemical > 0.01
          [ set pcolor (scale-color orange infection-chemical 10 0) ]
      ]
  ]
end

to move-dendritic-cells
  ask dendritic-cells [
    ifelse reporting = true
      [ uphill lymph-chemical ]
      [ right random 360
        forward 1
      ]
    set lifespan (lifespan - 1)
  ]
end

to check-d-cell-death
  let new-count 0
  ask dendritic-cells [
    if lifespan <= 0 [
      set new-count new-count + 1
      die
    ]
  ]
```

```
  setup-dendritic-cells new-count
end

to sample-tissue
  let infection-here 0
  ask dendritic-cells [
    if any? infection-sites-here and reporting = false [
      ask infection-sites-here [
        set infection-here infectious-signal
      ]
      set sampled-infectious-signal (sampled-infectious-signal + infection-here)

      if sampled-infectious-signal > reporting-threshold [
        set color red
        set shape "circle"
        set reporting true
      ]
    ]
  ]

  ask patches [
    if any? dendritic-cells-here with [ reporting = false ]
      [ set sampled sampled + 1 ]
  ]
end

to setup-effector-t-cells
  let reporting-num 0
  ask lymph-nodes [
    set reporting-num reporting-num + count dendritic-cells-here with [ reporting = true ]
    ask dendritic-cells-here with [ reporting = true ] [ die ]
    hatch-effector-t-cells reporting-num * t-cell-release-rate [
      set color gray
      set shape "target"
      set lifespan random-normal mean-t-cell-lifespan std-t-cell-lifespan
      right random 360
      fd 1
    ]
  ]

  setup-dendritic-cells reporting-num
end
```

```
to move-effector-t-cells
  ask effector-t-cells [
    uphill infection-chemical
    set lifespan (lifespan - 1)
  ]
end

to check-effector-t-cell-death
  ask effector-t-cells [ if lifespan <= 0 [ die ] ]
end

to clear-infection
  let t-cell-num 0
  ask infection-sites [
    set t-cell-num count effector-t-cells-here

    if t-cell-num > 0 [
      set infectious-signal infectious-signal - t-cell-num
      ask effector-t-cells-here [ die ]
    ]
  ]
end

to check-infection-site-death
  ask infection-sites [ if infectious-signal <= 0 [ die ] ]
end
```

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