WIRELESS SENSOR NETWORKS MOBILITY MANAGEMENT:
A PERFORMANCE CONTROL APPROACH

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy at the University of Cyprus

Recommended for Acceptance
by the Department of Computer Science

Sept, 2013
DECLARATION OF DOCTORAL CANDIDATE

The present doctoral dissertation was submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy of the University of Cyprus. It is a product of original work of my own, unless otherwise mentioned through references, notes, or any other statements.

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WIRELESS SENSOR NETWORKS MOBILITY MANAGEMENT:
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ΔΙΑΧΕΙΡΙΣΗ ΚΙΝΗΤΙΚΟΤΗΤΑΣ ΣΕ ΑΣΥΡΜΑΤΑ ΔΙΚΤΥΑ ΑΙΣΘΗΤΗΡΩΝ: ΜΕ ΤΗΝ ΠΡΟΣΕΓΓΙΣΗ ΤΟΥ ΕΛΕΓΧΟΥ ΑΠΟΔΟΣΗΣ

Ζήνων Ζήνωνος
Πανεπιστήμιο Κύπρου, 2013

Η αυξημένη χρήση των ασύρματων δικτύων αισθητήρων σε διάφορες εφαρμογές έχει δημιουργήσει έντονο ενδιαφέρον από πλευράς ερευνητών για συστήματα που πρέπει να παρέχουν συγκεκριμένες εγγυήσεις απόδοσης. Επιπλέον, στις μέρες μας υπάρχει έντονο ενδιαφέρον από τις βιομηχανικές επιχειρήσεις για να χρησιμοποιούν τα δίκτυα αισθητήρων για έλεγχο των διαδικασιών τους, λόγω κυρίως του χαμηλού κόστους εγκατάστασης και συντήρησης που μπορούν να προσφέρουν. Σε εφαρμογές όπου η απόδοση είναι εξαιρετικά σημαντική (critical applications), η παρακολούθηση σε πραγματικό χρόνο ενός κινητού κόμβου/χρήστη πρέπει να είναι πάντα διαθέσιμη, κάτι που απαιτεί την ύπαρξη ενός κατάλληλου πρωτοκόλλου κινητικότητας για τον έλεγχο της διαδικασίας μεταπομπής (handoff).

Στην παρούσα εργασία, στόχος μας είναι να δημιουργήσουμε ένα πρωτόκολλο διαχείρισης της κινητικότητας, που μπορεί να εφαρμοστεί σε κρίσιμες εφαρμογές και το οποίο θα μπορεί να διατηρήσει αποτελεσματική την συνδεσιμότητα του κινητού κόμβου ελέγχοντας τη διαδικασία μεταβίβασης από ένα κόμβο εξυπηρέτησης σε άλλο (handoff procedure). Το πρώτο βήμα αυτής της εργασίας ήταν να χαρακτηρίσουμε το μοντέλο της φυσικής διάδοσης του σήματος (radio propagation model) στο βιομηχανικό περιβάλλον με στόχο την ενσωμάτωσή της σε προσωπική συστήματος.

Η αρχική μας προσέγγιση βασίζεται στη χρήση μίας μόνο μεταβλητής για την αρχικοποίηση της διαδικασίας μεταβίβασης. Έτσι, υλοποιήθηκαν και αξιολογήθηκαν λύσεις που περιλαμβάνουν τη χρήση διάφορων μετρικών, όπως το RSSI, το Link Loss, το Burst Loss, το Simple Moving Average του RSSI, και του Link Loss και το Estimated Weighted Moving Average του RSSI και του Link Loss. Η δεύτερη μας προσέγγιση ήταν να χρησιμοποιήσουμε αρχές ελέγχου ασαφούς λογικής (fuzzy logic control) για να
σχεδιάσουμε ένα απλό, αποτελεσματικό, και αποδοτικό μη γραμμικό νόμο ελέγχου, προκειμένου να παράσχει ένα σύστημα που θα καταφέρει να ελέγξει τη διαδικασία μεταβίβασης και να παρέχει βελτιωμένη απόδοση. Έτσι, προτείναμε τη λύση Fuzzy Logic Mobility Controller (FLMC), η οποία φαίνεται να έχει υψηλές επιδόσεις συγκρινόμενη με όλες τις άλλες λύσεις.

Όσο αφορά τη διαδικασία της απόφασης και εκτέλεσης της μεταβιβάσεως (handoff decision/execution phase), χρησιμοποιήσαμε τρεις διαφορετικές επιλογές. Η πρώτη επιλογή ήταν η χρήση του RSSI με περιθώριο υστέρησης, η δεύτερη επιλογή που προτείνουμε είναι το Burst Loss Algorithm (BLA) το οποίο χρησιμοποιεί πολλαπλά σημεία προσάρτησης για να αποφασίσει το καλύτερο σημείο μεταβίβασης και η τρίτη επιλογή ήταν ένας συνδυασμός των δύο παραπάνω επιλογών.

Τέλος, προτείναμε ένα νέο μοντέλο κινητικότητας που είναι σε θέση να υποστηρίζει την κινητικότητα των κόμβων σε 6LoWPAN δίκτυα. Το μοντέλο αυτό περιλαμβάνει τη μορφή και το είδος των πακέτων που ανταλλάσσονται καθώς και τη λειτουργία του κινητού κόμβου. Παρέχεται αναλυτική αξιολόγηση της πρότασής μας συγκρινόμενη με άλλες λύσεις.

Η δυνατότητα εφαρμογής των προτεινόμενων λύσεων ελέγχθηκε σε πραγματικό βιομηχανικό περιβάλλον το οποίο ήταν ένα διαλιστήριο πετρελαίου, όπου η απόδοση του δικτύου επικοινωνίας είναι κρίσιμη, καθώς και χρησιμοποιούσας τον προσωμοιωτή COOJA ο οποίος τροποποιήθηκε με τέτοιο τρόπο ώστε να προσομοιώνει τη συμπεριφορά του διαλιστηρίου πετρελαίου. Παρά το γεγονός ότι η αξιολόγηση της προτεινόμενης λύσης πραγματοποιήθηκε με τη χρήση ειδικών υποδομών (π.χ. πρωτόκολλο TDMA MAC), οι λύσεις που προτείνονται είναι εφαρμόσιμες κάτω από οποιαδήποτε περιβάλλον αφού στηρίχτηκαν σε δυο γενικά αποδεκτές μετρικές όπως το RSSI και το Link Loss.
The growth of wireless sensor networks utilization has generated research attention in systems that need to provide certain performance assurances. Nowadays, there is also an increased interest from industrial operations to use sensor networks, due to the low deployment and maintenance cost that they can provide. A number of sensor network applications are envisioned to be applied to industry settings where the existence of mobile nodes (MN) is required. In critical applications, the real-time monitoring of a MN must always be available, something that requires the existence of a suitable mobility protocol to control the handoff procedure.

In this thesis, we aim to create a mobility management protocol that can be applied in critical applications and which will efficiently maintain the connectivity of the mobile node by controlling the handoff procedure (triggering and execution).

The first step of this work was to characterize the radio propagation model of the industrial setting with the goal to incorporate it into the scope of relevant simulators.

Our first mobility management approach was based on the use of single-metric based handoff triggering solutions. Thus, we implemented and evaluated solutions which include the use of metrics like the RSSI, Link Loss, Burst Loss, the Simple
Moving Average of the RSSI, and the Link Loss and the Estimated Weighted Moving Average of RSSI and Link Loss. Our second approach was to use fuzzy logic control principles to design a simple, effective, and efficient non-linear control law, in order to provide a system that will manage to control the handoff triggering procedure and provide improved performance. We proposed the Fuzzy Logic Mobility Controller (FLMC) solution which is shown to outperforms all other solutions.

Regarding the handoff decision/execution phase, we used three different options. The first option was the use of the RSSI with hysteresis margin, the second option was our proposed Burst Loss Algorithm (BLA) using multiple attachment points and the third option was a combination of the two aforementioned options.

Finally, we proposed a new network-based mobility model able to provide mobility support in 6LoWPAN networks. This model includes the proposal of the mobility signalling, the packet format and the operation of the MN. Analytical evaluation of our proposal comparison with other solutions is provided.

The applicability of the proposed solutions was established in both an oil refinery industry setting where performance is critical and the COOJA simulator which was modified to match the refinery testbed behaviour. Although that the evaluation of proposed solution was performed using specific infrastructure (ex. TDMA MAC protocol), the solutions are applicable to any setting that can provide the two general metrics named RSSI and Link Loss.
ACKNOWLEDGEMENTS

This dissertation would not have been possible without the guidance and the help of several individuals who, in one way or another, contributed to the preparation and completion of this study. Firstly, I would like to thank my thesis supervisor, Assistant Professor Dr. Vasos Vassiliou. I am very grateful for his continuous and inspiring guidance during my studies at the University of Cyprus. Without his guidance and persistent help this dissertation would not have been possible.

Furthermore, I would like to express my gratitude to Dr. Chrysostomos Chrysostomou Lecturer at the Frederick University. With his enthusiasm, his inspiration, and his great efforts to explain things clearly and simply, he helped to clarify and highlight different aspects of the proposed fuzzy logic approaches.

I would like to acknowledge the academic and technical support of the Department of Computer Science and especially the Networks Research Lab (NetRL), which have provided the support and equipment I have needed to produce and complete my thesis. I am indebted to all student colleagues, members of NetRL, for providing a stimulating and fun environment in which I was able to grow and learn.

This work was made possible by the financial support of the GINSENG: Performance Control in Wireless Sensor Networks project funded by the 7th Framework Programme under Grant No. ICT-224282.
I wish to express a very special thanks to my father Andreas and my mother Eleni for providing a loving and caring environment for me from the very beginning of this study until the end.

Lastly, and most importantly, I wish to thank my beloved wife Elena who has generously and unconditionally supported me with her love and encouragement all these years of my studies, which led to the completion of my Ph.D. thesis. I am also thankful to my two sons, Andreas and Marios-Valantis for their understanding of my “not nows” and cheering me on when I was disheartened.
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Acronyms

CI  Computational Intelligence
DAD  Duplicate Address Detection
DTC  Dynamic Topology Control
EWMA  Estimated Weighted Moving Average
FIE  Fuzzy Inference Engine
FLC  Fuzzy Logic Control
FLMC  Fuzzy Logic Mobility Controller
IoT  Internet of Things
IP  Internet Protocol
IPv6  Internet Protocol version 6
IWSN  Industrial Wireless Sensor Networks
JB  Junction Boxes
MAC  Medium Access Control
MIPv6  Mobile Internet Protocol version 6
MN  Mobile Node
M2M  Machine to Machine
ND  Neighbour Discovery

PAN  Personal Area Networks

PMIPv6  Proxy Mobile Internet Protocol version 6

PRR  Packet Reception Rate

RSSI  Received Signal Strength Indicator

SMA  Simple Moving Average

SN  Static Node

TDMA  Time Division Multiple Access

UC  Urban Computing

WSN  Wireless Sensor Networks

6LoWPAN  IPv6 Low Power Wireless Personal Networks
Chapter 1

Introduction

In recent years, applications of wireless sensor networks have evolved in many domains, largely due to their large applicability and development possibilities, and also progress in many areas related to hardware, especially in low-power wireless communications. The majority of the research in WSNs assumes a large number of sensors that are randomly deployed in static positions. Thus, node mobility and network performance assurances were not considered essential. In addition to the diverse applications, sensor networks pose a number of unique technical challenges due to their ad-hoc deployment, unattended operation, and dynamic environment changes. Most sensor applications require the deployment to be infrastructure-less, without any human intervention. It is the responsibility of the sensor network to be adaptable to any physical changes like the addition of extra nodes or the failure of some of them. In addition, there is only a finite source of energy, which must be optimally used for processing and communication. Nowadays, several application sectors like healthcare, industrial automation, urban sensing/computing, and
vehicular sensor networks assume and incorporate the use of mobile nodes. Due to this, it is expected that the host, device and network mobility will be common in the near future. Numerous applications of mobility, of WSNs and of their combinations can be foreseen. However, along with numerous positive aspects, mobility in WSNs also means difficult challenges. These include topology changing, mobility management, network coverage, network lifetime, routing protocols, security, data reliability, quality of service, and on-time data delivery. Several theoretical studies have been performed where mobile nodes have been used in order to address a number of critical considerations such as connectivity, network lifetime, coverage, congestion control, and event/target tracking. Mobility, was therefore seen as a part of a procedure which can make the network to perform in an improved manner.

1.1 Motivation

In current WSNs applications there is an increased need for the support of mobile nodes. An example application is the case of personnel safety in hazardous industrial environments, such as an oil refinery. In such environments, the pollution is usually high and situations may arise where employees have to work in highly hazardous areas. Cleaning empty storage tanks is the most common such activity. Since personnel move around the refinery, there should be a way to continuously monitor their physiological condition. To do so, a mobility management tool is needed, which will be able to provide real time monitoring of the physiological condition of the workers. Another example where this technology could be applied is e-health, where
a mobility management protocol could provide remote and continuous access to the patients’ physiological parameters by the physicians. This technology could also be applied in monitoring people suffering from various forms of disabling diseases. Many elderly people have to leave their homes and move into nursing homes when the risk of living alone becomes too high. Since these people need to maintain their mobility, an appropriate mobility management framework to handle their on-body sensors is necessary.

In addition, the introduction of 6LoWPAN on moving embedded devices, enables the vision of the Internet of Things (IoT) and Urban Computing (UC), where both are expected to transform ubiquitous spaces into intelligent environments in the near future. 6LowPAN tries to combine the IP technology with any low power wireless device. The motivation behind this attempt is to exploit the benefits offered by the use of the legacy IP protocol. Those benefits include the easy interconnection with other IP networks, the reuse of existing internet infrastructure, the application of the well-known IP-based technologies to sensor networks, and the use of existing power monitoring and diagnostic tools. The challenge in supporting IP protocols in WSN is to overcome the limitations experienced by sensor networks like lower power consumption, low duty cycles, limited bandwidth, and reduced reliability. Despite that mobility management protocols in IPv6 is a topic that was studied in detail, the applicability of the existing solutions in LoWPAN is disputed. Thus, the proposed techniques to support mobility could be applied to 6LoWPAN.
Consequently, this work will provide practical solutions towards real-world deployments, by proposing a mobility protocol that can provide performance guarantees. The applicability of our solution will be established in a real industrial setting where performance is critical.

1.2 Problem Statement

In spite of all the potential of WSNs, real deployments are rare, and virtually all have considerable limitations when user mobility is concerned. Clearly, there is a mismatch between research and real-life applications, and work on mobility does not produce results that are directly applicable to real testbeds, which points to the need to provide more practical steps towards real world deployments and services.

Analysis of the state of the art in this area reveals that there are a whole raft of projects and initiatives covering a wide spectrum of related research challenges, technological problems and collaboration activities in Wireless Sensor Networks. However, the point of departure of this work and the key thesis, is that there is no protocol designed and evaluated to support the mobile process in critical environments. This issue is considered of utmost importance for today’s real-world applications.

Therefore, the problem that this thesis tries to solve is to provide a suitable mobility management protocol in order to support critical applications with performance requirements and to achieve seamless connectivity by controlling the handoff procedure in a real industry setting.
The formulation of a solution for a specific critical application will need to address the wireless communication design in the context of the application as well as in the context of the application’s environment, e.g., RF industrial environment. As a consequence, an additional issue that we need to investigate is the modelling of the radio propagation model in an industrial environment.

1.3 Approach

The main target of this thesis is to provide mobility support for critical applications with specific performance requirements. The uniqueness of this work is the use of a real industrial setting (oil refinery) as the evaluation environment, something which poses new challenges regarding the design of mobility support. The fact that there are no other similar solutions provided by the two well-known industrial standards namely WirelessHart [6] and ISA100 [7] makes this work of utmost importance.

Our approach to provide mobility support for mobile nodes resides on the fact that we have to control the handoff procedure, which means that at a first stage we have to control the handoff triggering procedure. Due to the unpredictability of the environment, we cannot rely on a single specific metric and we target a solution that can combine information using more than one metric. Since our environment is expected to perform dynamically, we decided to use fuzzy logic to control the triggering procedure. The selection of fuzzy logic is supported by the fact that it can handle multiple inputs with minimum overhead. Therefore, an intelligent
controller is used, based on fuzzy logic, in order to help mobile sensor nodes to
decide whether they have to handoff to a new position or not. We use fuzzy logic
control principles to design a simple, effective and efficient non-linear control law, in
order to offer inherent robustness with effective control of the system. The proposed
fuzzy mobility controller could be used with any underlying technology, for example
in 6LoWPAN.

Despite the selection of Fuzzy Logic-based solution, the lack of similar work
forced us to propose and implement numerous solutions that rely on a single metric
(like the RSSI and the Link Loss), in order to be able to compare the different
approaches and conclude about the suitability and applicability of each solution.
Therefore, initially we have designed a set of handoff procedures based on RSSI and
Link Loss and then designed a Fuzzy Logic-based solution in order to improve the
performance.

Due to the limitations of the sensor nodes it was decided, at the beginning of
this work, that the design of the mobility support should use existing information
as much as possible in order to avoid the introduction of additional overhead to the
system. Any necessary new functionality was to be considered only if the overhead
to the existing system would be negligible. In addition, our target was to provide
a distributed solution, meaning that there should not be no central entity with full
knowledge of the system which would decide about the handoff procedure. There-
fore, all the information used is locally available at each node and no communication
overhead is added. The distributed approach allows the system to adapt quickly to
disturbances or changes within the network in real-time. This approach also includes some other critical targets like learning how the testbed environment operates. To do so, a number of long-term experiments using fixed nodes were ran so that to have a clear vision of the testbed behaviour. In addition, effective dynamic ways of building and controlling the topology were proposed so as to support the movement of the mobile node to different topology places.

Figure 1 summarizes the general implementation strategy that was followed in order to accomplish the several tasks of this thesis. Since the environment is unpredictable and unknown it was expected that the cycle depicted in Figure 1 will be repeated several times until we reach an acceptable performance. In other words, several optimizations are expected for the proposed mobility solution.

![Figure 1: Implementation Approach](image)

1.4 Contribution

In this section, we describe the contribution of the thesis while in Appendix A we provide a complete list of publications and submissions stemming from the work
in this thesis. The main contribution of the thesis is given in four chapters, Chapter 3 to Chapter 6. The outline of the contributions is as follows:

1. An intelligent controller (FMLC), based on Fuzzy Logic is proposed. This controller enables sensor mobile nodes to intelligently decide whether they have to trigger the handoff procedure and perform the handoff to a new position or not.

2. The proposal and the implementation of numerous mobility control solutions that rely on a single metric (like the RSSI, Link Loss, Burst loss), in order to be able to compare the different approaches and conclude about the suitability and applicability of each solution.

3. Examination of the commonly-used Received Signal Strength Indicator (RSSI) based handoff decision solution in WSNs in order to investigate the best hysteresis margin and to discover the best window size of the Simple Moving Average (SMA) and Exponential Weighted Moving Average (EWMA) extension.

4. The proposal of a new handoff decision algorithm, named Burst Loss Algorithm (BLA) which is based on burst packets acknowledgements and the use of multiple attachment points.

5. The use of a real industrial setting (an oil refinery) as the evaluation environment of the different solutions.

6. The use of different evaluation scenario settings that help us to define the importance of the proposed solutions. These scenario settings include: different
threshold value to initiate the trigger, different sensor nodes’ placement, different radio propagation models, different number of available new connection points, different application settings (data rate), different mobility models, and different number of sensor nodes. All these different settings helped us to decide about the global applicability of the proposed solutions.

7. The proposal of a simple adaptive thresholding FMLC which enables the MN to adapt the threshold based on the current network conditions.

8. The introduction of two evaluation metrics that are considered crucial for the decision of the best solution. These metrics are the on-time triggering, which indicates if the MN initiates (triggers) the handoff on-time when the one-hop link quality between the MN and the attachment node is not sufficient, and the handoff effectiveness which indicates if the handoff was correctly performed.

9. The proposal of a new network-based mobility solution for 6LoWPAN able to reduce the involvement of the MN in the handoff procedure.

10. The characterization of a radio propagation model that was designed based on the oil refinery setting. The integration of this propagation model to COOJA simulator provided us the opportunity to perform extensive experiments, something which was not feasible to achieve when the testbed setting was used.

1.5 Structure of the report

The current thesis is organized in the following manner:
In Chapter 2 the background information and the mobility related works are presented. We focus on mobility management in different layers, the description of applications that required mobile users, the types of the mobility models, the handoff process in mobile networks, and an overview of the topology control in sensor networks.

In Chapter 3, we introduce the system setup and architecture of the proposed solution. Since our target is to provide mobility support in industrial environments, a definition is given in this chapter of the characteristics of the specific industrial environment used (oil refinery) and the mobility scenario requirements. We used the long-term data from the refinery and, based on the lessons learned from our initial experimentations, we concluded that a key issue for the correct proposal and development of the mobility solution was to define the refinery radio propagation model. By integrating the refinery radio propagation model in simulation tools we had the opportunity to perform extensive experiments, something which was not feasible to achieve when the testbed setting was used.

In Chapter 4 we investigate both handoff phases (triggering and decision) in WSNs. We focus on the choice of single-based parameters and the ways of measuring them (e.g. Simple Moving Average (SMA) and Exponential Weighted Moving Average (EWMA)) in order to support the handoff triggering and decision process. In order to investigate the handoff procedure, we first implement and test hard handoff approach and then we proceed with the no-disruption handoff approach. In this chapter, we introduce two evaluation metrics that we consider as crucial for
the decision of the best solution. These metrics are the on-time triggering, and the handoff effectiveness. We propose and evaluate a new handoff triggering mechanism, named Burst Loss Algorithm (BLA), that is based on local link loss characteristics and a new handoff decision mechanism that is based on burst packets acknowledgments. We evaluate the performance of the triggering and handoff decision solutions in terms of the packet losses, on-time triggering and effectiveness of the handoffs considering their possible overhead.

Then, in Chapter 5 a novel, intelligent controller, based on fuzzy logic, is proposed to be applied, in order to support the mobile workers scenario and to help sensor mobile nodes to decide whether they have to initiate the handoff to a new position or not. We use fuzzy logic control principles to design a simple, effective and efficient non-linear control law, in order to offer inherent robustness with effective control of the system. The approach taken had greater applicability to any WSN industrial environment or testbed setting with mobility requirements, due to the fact that it was designed based on network state parameters that are available to all sensor mobile nodes. The main idea is that if the fuzzy logic control is designed with a good (intuitive) understanding of the system to be controlled, the limitations due to the complexity system’s parameters introduced on a mathematical model can be avoided. The selection of fuzzy logic system was based on its simplicity and the fact that since it processes experts-defined rules governing the target control system, it can be modified to improve system performance. In addition, it can control non-linear systems (such is our system) that would be difficult or impossible to model
mathematically. In order to compare the Fuzzy Logic-based solution with the single metric-based solutions we use a set of evaluation cases with different parameters like the decision point threshold $P_{\text{threshold}}$, the physical and logical topology and, at last, different radio propagation model. Finally, we adaptively select the decision point threshold based on performance feedback.

Chapter 6 proposes a new network-based solution to support mobility of the users in 6LoWPAN networks. To do so, we introduce an entity called, 6LoWPAN proxy agent (PA). The idea behind this is to force the 6LoWPAN PA to be responsible for MNs mobility signalling and operation with the Home Agent (HA) and just inform the MN, when necessary, to handoff to a new serving proxy.

Finally, Chapter 7 summarizes the conclusions of the numerical evaluations presented in this thesis and identifies opportunities for future work.
Chapter 2

Background

With the advancements in wireless communications and with the rapid growth in the number of mobile entities, mobility management is one of the most important and challenging problems for wireless mobile communication. Mobility management deals with all actions that must be taken in a network so that to support the movement of mobile users without losing connectivity. This is true in both infrastructure-based technologies (cellular, WLAN) and infrastructure-less types (ad-hoc, vehicular, sensor). In all cases when a mobile user/node moves to a new location it has to establish a new radio link with the target base-station/access-point/neighbor and release the connection with the previous, in a process called handoff. A basic handoff process consists of three main phases: (a) measurement phase, dealing with the mechanics of measuring important parameters and (b) the decision phase, dealing with the algorithm parameters and handover criteria [8], and (c) execution phase dealing with the executions of the handoff.
While mobility management is a well understood and researched topic in cellular telephony and WLANs, it is still a challenging topic in wireless sensor networks (WSN). WSNs promise fine-grain monitoring in a wide variety of environments and are expected to be deployed in difficult and often inaccessible environments, which from the communication perspective, are also usually harsh. WSNs are usually expected to be densely deployed, with a large number of nodes within communication range, which exacerbates the communication problems. An emerging application area that combines all the issues mentioned above and, in addition, poses significant performance requirements on the networks and protocols is the use of WSNs in industrial and manufacturing settings, or in general in settings where critical information needs to be transmitted and critical applications need to be operating [9]. It is, therefore, not difficult to envision scenarios within such demanding applications and settings where mobility would also be required [10][11].

The handoff procedure introduces some extra challenges to the mobility management function. One challenge is the triggering of the handoff at the right time to enable the MN to change its attachment point on time. The actual decision of the handoff to a new attachment point is another challenge of the mobile wireless networks. Both aforementioned challenges contribute to the major challenge on how to implement handoffs in wireless networks with minimum handoff latency and packet loss.
2.1 Wireless Sensor Networks Applications

Wireless sensor networks are currently receiving huge attention as a basic tool to detect emergency events or monitor physical parameters of interest, such as radiation, pollution, temperatures, pressures, and so on. The traditional WSN application is environmental monitoring, where static sensor arrays are deployed to collect sensor readings from large or remote geographical areas to a central point (or base station, sink). Therefore, algorithmic research in WSN has mostly focused on the study and design of energy-efficient and scalable algorithms for data transmission from the sensor nodes to the base station. Recently, the WSN applications have undergone a paradigm shift from static to more dynamic environments, where nodes are mobile, as they are attached to people, animals and moving objects. Examples of applications that require the existence of mobile nodes are the following:

2.1.1 Healthcare monitoring

Healthcare monitoring and biofeedback of patients in health facilities and in their homes is one of the most important applications of sensor networks. WSN can be used to detect abnormal physiological parameters values or uncommon body positions and generate and transmit an alarm message (Figure 2). Monitoring of hospitalized patients is a daily routine in infirmaries. Nowadays, this task is performed by medical staff that periodically gathers the values collected by body sensors close to the patients. The use of new technologies can improve the access to this data remotely and in real-time. This continuous access also allows a more effective
monitoring of these patients and a more rapid response in case of abnormal values of the controlled physiological parameters.

Figure 2: WSN Healthcare Application

2.1.2 Fire Detection

Forest fires are one of the most important factors that threaten the ecological balance in several countries. In order to protect forests, a WSN could be deployed to detect forest fire in its early stages. A number of nodes need to be pre-deployed in a forest (Figure 3). Each node can gather different types of information from sensors, such as temperature, humidity, pressure and position. All sensing data is sent by multi-hop communication to the control center via a number of gateway devices distributed throughout the forest. The gateways will have connectivity to mobile
networks, e.g. UMTS, and will be positioned so as to reduce the number of hops from source of fire detection to the control center. It may also be possible in this scenario that mobile forest patrol units can also act as mobile gateways, collecting environmental data as they traverse through the forest.

Figure 3: WSN Fire Detection Application

2.1.3 Industrial applications

Using wireless technologies in industrial automation makes it possible to have access to more information related to the production processes. An important advantage of using wireless technology and sensor networks is the ability to support asset tracking. A typical scenario of asset management is shown in Figure 4 where a forklift is moving goods between warehouses and an assembly facility. A wireless embedded network in such an application may be used in several ways, including
tracking the forklift itself, the goods being moved, and the personnel in the plant.
All of these uses of the wireless network require us to deal with node mobility.

In addition to the asset management scenario a possible industrial scenario that
includes mobile nodes is the personnel monitoring (Figure 5). Usually, industrial
fields are hazardous environments with a lot of health dangers. Consider the case
of a refinery industrial environment where the employees enter hazardous areas (e.g.
tanks) of the refinery for regular maintenance and may faint because of the toxic
atmosphere and residues of their previous contents. Therefore, it is important to
monitor the health of the employees that enter such environments to make sure
they remain conscious. Sensors can be attached to these employees to monitor their
orientation and send this information to the control center. To perform this task,
the employees must be equipped with special suits and tools to protect them from
that environment. When a person’s orientation is horizontal for an unusually long
period of time (indicating a fall or unconsciousness) an alarm can be signalled to the control center to notify health and safety staff of a possible emergency.

![Image of a sensor network](image)

Figure 5: WSN Personnel Safety [2]

### 2.2 Mobility in WSNs

A wireless sensor network is a network connecting many, distributed objects called sensor nodes. A sensor node is a low power, low cost, multi-functional device that consists of sensor(s), a data processing component, communicating components and application-dependent components. A WSN is usually applied to applications where they collaboratively monitor, instrument and respond to physical or environmental conditions where they are needed. Examples of such conditions are temperature, pressure, pollution etc. Early studies on WSNs were based on mesh (unstructured) topologies consisting of homogeneous sensor nodes that were often deployed randomly. These WSNs were mostly monitoring applications without strong requirements on timeliness, reliability and security since they collected non-critical data.
Despite that, nowadays new application sectors require the collection of critical data (could be health related, security/alarmed related etc) and they assume the presence of mobile users, thus the existing monitoring tools are not sufficient enough. Critical data are usually related to harsh and unpredictable environments so techniques to respond to the dynamic changes of the environment are required. Thus, to deal with such changes, mobility management approach should be followed. In order for mobility management to perform correctly two main functionalities must be handled: the topology/placement control and the handoff management.

Topology control is one of the most important operations in a WSN environment, since it affects the performance provision of the WSN. Topology control techniques may result in (a) generating a WSN with the required properties (e.g. connectivity, coverage), (b) increasing network capacity, (c) maximizing the efficiency of data gathering, (d) reducing energy requirements, and (e) mitigating congestion. Relocation of nodes or placement of new nodes to a planned location may result in energy conservation and/or congestion avoidance. Selecting the best location to place new nodes, the velocity and mobility pattern when relocating mobile nodes, the transmission power of the transceivers, the network connectivity degree, and the interference caused from neighbouring nodes are some of the properties taken into consideration by the topology control algorithms.

Handoff management is the process by which a mobile node keeps its connection active when it moves from one access point to another. The handoff process can be divided to two main stages: the first is the triggering of the handoff where the
second is the discovery of a new connection point and the handoff connection to this point.

2.3 Types of mobility in WSNs

Mobility in WSNs can be classified in three types: node, sink and event mobility.

1. Node Mobility We can classify node mobility based on the node movement:

   (a) Device movement within a single Wireless network domain (Intra-PAN): This scenario is probably the most common in WSNs architectures. The sensor node moves within the domain without losing the connectivity with the Sink node.

   (b) Device movement between multiple Wireless network domains (Inter-PAN): Sensor nodes move between different sensor networks, each one

Figure 6: WSN Intra mobility
with its Sink node responsible to configure and manage all the aggregated devices.

Figure 7: WSN Inter Mobility

In Intra-mobility the sensor node moves within the same network domain, remaining reachable through the same network, address even after changing the attachment point. In contrast, in inter-mobility the sensor node moves between different network domains, which require a network address update to keep accessible. The handoff between two networks, or between two different attachment points within the same network can be of two types: soft or hard. Soft-handoff occurs when the sensor node moves between different network domains but within networks operating in the same frequency, allowing the establishment of mutual network addresses and therefore maintaining more than one connection at the same time. Hard-handoff, which is considered the most critical case, occurs in a situation where no mutual connection can be
established, such as in the case where the sensor node moves between networks operating in different domains and communication channels, forcing the node to firstly disconnect from the old network before connecting to the new one.

2. **Sink Mobility** Based on [12], the sink mobility can be classified (Figure 8) into Mobile Base Station (MBS)-based, to Mobile Data Collector (MDC)-based, and to Randezvous-based. The categorization is done with respect to the sink mobility pattern as well as the wireless communication methods for data transfer. The concept of mobile sink was introduced in order to address several problems of stationary sink deployments arising from long distances between sink and source nodes.

![Figure 8: WSN Sink Mobility](image)

- **Mobile Base Station (MBS):** The primary objective is to move the sink in the network to distribute energy consumption evenly. Mobility of the sink increases the coverage and decreases the hops to reach each node.
- **Mobile Data Collector (MDC):** reflects the capacity of the more powerful nodes (Sinks or other) to perform on-demand collection, avoiding data travel through several hops. The existing MDC solutions can be classified
based on the mobility pattern of the sink node. These patterns include the random mobility where the MDCs move in random patterns as proposed in [13], the predictable mobility where an MDC’s movement pattern is known, as presented in [14] and finally the controlled mobility where the MDC’s movement is actively controlled in real time, as proposed in [15].

- **Rendezvous:** The Rendezvous-based solution is a hybrid of both solutions: MBS and MDC [12]. Data is accumulated at designated sensor nodes. These designated nodes buffer collected data until they are relayed to an MDC something that increases the data latency. Solutions that propose collection of data from designated sensor nodes by a mobile device constitute the class of rendezvous-based solutions. These carry properties of both MDC as well as MBS-based solutions: As in MBS-based solutions, data is relayed over multiple hops before being delivered to the mobile device. Furthermore, generated data is buffered for a relatively long period before it is relayed, as in MDC-based solutions.

3. **Event Mobility** In the event-based mobility the targeted events or objects are mobile (ex. tracking an elephant Figure 9). The mobility of the event introduces severe problems to the network since the initial deployment of the sensors may not guarantee the full monitoring of the event and the connectivity of the network. Therefore, to satisfy such a requirement, the deployment of a large number of sensor nodes is necessary, something that it is not economically
feasible. In addition, the dynamic changes in the monitoring area and the existence of obstacles could make the problem become more difficult.

![Figure 9: WSN Event Mobility [3]](image)

### 2.4 Mobility models

Mobility models represent the movement of mobile users, and how their location, velocity and acceleration change over time. Such models are frequently used for simulation purposes when new communication or navigation techniques are investigated. A mobility model should mimic the movements of real nodes. The mobility models are based on entity movement or group movement. The most common mobility models of both categories are presented below.

#### 2.4.1 Entity-based mobility models

1. **Random Walk Mobility Model**

   This is the most common mobility model used for performance evaluation. Einstein first described this model in 1926 and it was originally proposed
to emulate the unpredictable movement of particles in physics. Currently, the random walk model has been used to investigate a broad set of different system parameters, for example the mean cell sojourn time in cellular networks. In the Random Walk Mobility Model the nodes change their speed and direction in either a predefined constant time interval or a constant distance travelled. The new speed is chosen from predefined ranges \([\text{speed}_{\text{min}}, \text{speed}_{\text{max}}]\) and the direction from ranges \([0, \pi]\). If the node reaches the simulation boundary it is bounced back to the simulation field with an angle determined by the incoming direction. This model is a stateless model meaning that the future direction and speed is not depended on the past directions and speeds. In addition, the movement of the node does not depend on the movement of other nodes in the field. The drawback of this model is that it can cause unrealistic movement such as sudden stops, sharp turns, and sudden acceleration. In real life scenarios the direction change is usually smooth and the speed accelerate incrementally.

2. **Random Waypoint Mobility Model**

This model is similar with the Random Walk Mobility Model with the difference that a pause time is introduced. The MN starts by staying in one place until the predefined pause interval is expired. After that, it selects speed and direction as in the Random Walk model and travels towards the chosen destination. Upon reaching the destination, it randomly selects another destination in the simulation field and travels toward it. Using the Random
Waypoint Mobility Model the probability of choosing a new destination which is located in the centre of the simulation area, or requiring travel through the middle of the simulation area, is high. This characteristic it is called Density Wave phenomenon. The concern in this model is what values to assign to the speed and the paused period. The combination of small speed and long pause time will result in a relatively stable topology, whereas in case of high speed and small paused period the topology is highly dynamic. Changing these two parameters will create various types of mobility scenarios. A problem that can occur by using this model is the density wave phenomenon where nodes tend to cluster near the centre region of simulation field and move away from the boundaries. Due to its simplicity and wide availability, the main application of the Random Waypoint Mobility Model is as a benchmark model to evaluate the MANET routing protocols.

3. Random Direction Mobility Model

This model is created to give solutions to the density wave phenomenon of the Random Waypoint Model. In order to avoid the clustering of nodes in one simulation area the MN is forced to travel to the edge of the simulation area before changing direction and speed. As soon as the boundary is reached, the MN stops for a certain period of time, chooses another angular direction (between 0 and 180 degrees) and continues the process.

4. Gauss-Markov Mobility model The Gauss-Markov was originally proposed for the simulation of a Personal Communication Systems (PCS) [16];
however, this model has been used for the simulation of ad-hoc network protocols [17]. In Gauss-Markov model the velocity of the MN is assumed to be correlated over time and model as a stochastic Gauss-Markov process. We could say that the Gauss-Markov Model is a mobility model with temporal dependency of velocity meaning that the current velocity of a mobile node may depend on its previous velocity. At each interval the next location is calculated based on the current location, speed and direction of the movement. In order to ensure that a MN does not remain near an edge for a long time, the MN is forced away from an edge when it moves within a certain distance of the edge.

2.4.2 Group-based mobility models

1. Column Mobility Model

This mobility model can be used in searching and scanning activity, such as destroying mines by military robots. Sets of MNs move around a given line, which moves forward. An initial reference grid forming a column of MNs is defined. Each MN is then placed in relation to its reference point in the reference grid. The MN is then allowed to move randomly around its reference point via an entity mobility model.

2. Nomadic Community Mobility Model

This model applies to the scenario where a group of nodes move together. This model could be applied in mobile communication in a conference or military
application. The whole group randomly selects a new location to travel. In addition, each MN node inside this group maintains a space around a reference point that moves in random ways. To do so, each MN uses an entity-based model to perform this movement. When the reference point of the group is changed all the MNs in the group travel to the new area.

3. Reference Point Group Mobility Model

In this model each group has a center which is the logical center or the group leader. The movement of the leader (center) determines the mobility of the whole group. At each instance, every node has a speed and direction which is derived by randomly deviating from that of the group leader. This general description of group mobility can be used to create a variety of models for different kinds of mobility applications. With appropriate selection of predefined paths for group leader and other parameters, the RPGM model is able to emulate a variety of mobility behaviours. RPGM model is able to represent various mobility scenarios including the following:

• In-place mobility model: the entire field is divided into several adjacent regions. A single group exclusively occupies each region. One such example is battlefield communication.

• Overlap mobility model: different groups with different tasks travel on the same field in an overlapping manner. Disaster relief is a good example.
• Convention mobility model: this scenario is to emulate the mobility behaviour in the conference. In a convention, several groups give demos of their research projects/products in separate but connecting rooms. A group of attendees roams from room to room. They may stop in one room for a while and then move on to another room.

2.5 Mobility management at different layers

Mobility management in wireless networks is a complex issue and usually involves different layers of the communication protocol stack (Figure 10). Several proposals have appeared that attempt to control and accelerate the handoff procedure. Those proposals can be classified based on the layer that the mobility management is handled: at the networks layer, at the Data Link layer, or as a cross-layer solution.

![WSN Communication stack](image)

Figure 10: WSN Communication stack
The network layer mobility management protocols use messages at the IP layer, and are agnostic of the underlying wireless access technologies while data link layer mobility mechanisms provide mobility-related features in the underlying radio systems.

### 2.5.1 IP-based Mobility

Recently, there have been attempts to integrate Internet protocol (IP) with the WSN. The motivation behind this attempt is to exploit the benefits that the use of IP protocol can offer. The most significant effort is performed by IETF that created the 6lowPAN working group, which aims to develop the support of IPv6 over the standard IEEE802.15.4, in order to import the well known capabilities of IPv6, such as Neighbor Discovery (ND) or Mobile IP (MIPv6) into low power devices. In RFC 6568 [18], the authors describe some real life design and application spaces for 6LoWPANs which show the importance of 6LoWPANs in near future. Mobile IPv6 (MIPv6) [19] is the global mobility protocol that aims to maintain IP connectivity for the mobile node (MN). In MIPv6, when a MN moves from one network to the other, it forms a care-of address (CoA) based on the prefix of the foreign link. Thereafter, the node sends the Binding Update (BU) to its home agent (HA). Enhancements of MIPv6 is the HMIPv6 [20]. In HMIPv6, a new entity called Mobile Anchor Point (MAP) is introduced which acts as a local HA of the MNs. In this way there is a separation between global mobility and local mobility. The main drawback of the IP-based mobility solutions is that there is an inaccessible time period because of link
switching and IP protocol operations like Care-of Address (CoA) generation. These protocols handle mobility management by exchanging binding messages. Unfortunately, they have not solved how to minimize the handover delay. In [21] authors proposed an IP-WSN architecture solely based on PMIPv6 for energy efficient mobility of individual sensor nodes or a group of sensor nodes. In this paper, they present the functional architecture, and the respective message formats, sequence diagram, network model. They evaluate the performance of the proposed protocol architecture compared to MIPv6 and PMIPv6, which actually it is the main drawback of their work since the performance of the proposed solution it was expected to outperform MIPv6 and PMIPv6. In [22], authors propose a network mobility protocol called NEMO, to support 6LoWPAN network mobility, but they do not consider the 6LoWPAN node mobility. In [23] a network assisted mobility solution for 6LoWPAN is proposed. This scheme helps to predict the future location of the MN and buffers its packets for small amount of time, in order to prevent packet loss. In [24] authors present an architecture to support medical sensor networks based on 6LoWPAN, where they have defined a protocol to carry out inter-WSN mobility.

2.5.2 Data Link Layer (MAC-based) Mobility

To support the mobility of nodes it is often useful to control the process from the MAC Layer. Many researchers have designed and evaluated new algorithms to optimize the duty cycle scheme. Examples of mobility-aware MAC protocols for
WSN solutions which are related to our work are: the MS-MAC [25], MA-MAC [26] and MobiSense [27].

MS-MAC is the mobility extension of contention-based SMAC protocol and it tracks the RSSI values from SYNC messages to identify the movement of a node. In case of movement, the node broadcasts a SYNC message containing its schedule. When neighbouring nodes receive this message, they create an active zone by adjusting the synchronization frequency. As a result, the mobile node will be awake as much as possible leading to a successful connection set up process. The main drawback of this solution is the significant increase of energy consumption of the neighbour nodes.

MA-MAC is an extended version of XMAC which enables a node to sleep most of the time and switch on the radio for receiving the incoming packets periodically. MA-MAC detects mobility through the received signal strength of ACK packets during communication and switches from unicast to broadcast to interleave data communication with neighbour discovery. To support mobility, MA-MAC defines two distance thresholds. The first threshold prompts a node to initiate a seamless handover, whereas the second threshold sets an upper limit to the distance that should be travelled before the mobile node has established a link with a new relay neighbour. During mobility, if a transmitter detects that the distance between the receiving node and itself exceeds the first threshold, it enters into a discovery state and begins to search for an intermediate neighbour along the way to the base station. To do so, the transmitter broadcasts data packets in which handover requests are
embedded. If it receives at least one of ACK packet from a new node before it completes the second distance threshold, the transmitter enters into a handover state to resume data transmission to the newly discovered node. The transmitter enters into a sleep state otherwise. A critical issue of this solution is the selection of appropriate threshold values.

In MobiSense nodes are organized into clusters, in which static nodes act as cluster-heads and mobile nodes move between them. To increase the network throughput and to simplify the network management, the cluster-heads operate in different channels. The aim is to reduce the interference between the clusters and to allow the cluster-heads to dynamically schedule traffic locally. All cluster-heads send synchronization packets at the beginning of each frame to inform mobile nodes about the changes in their uplink and downlink transmission. As a result, by listening to these slots, mobile nodes that want to join the network or handover from one cluster to another can rapidly gather network information and build the prioritized lists of access points. After determining the new cluster, a mobile node randomly selects an access mini-slot and sends its own join request message.

2.5.3 Cross-layer mobility

Standard layered-architectures have well-defined interfaces between network layers, subsequently allowing protocols and services within layers to be exchanged without the need to change other layers of the stack. However, this also limits the information flow between layers and restricts layers to use specific communication
interfaces, thereby disabling potential side channels for information retrieval. Cross-layer design allows merging existing layers, to make communication more efficient. This is more important in embedded devices and small scale systems. Therefore, the cross-layer protocols use information from different layers (usually combine network and link layer information) and they are more common for handoff management. These mobility protocols aim to minimize the data loss rate and delay time during switching so that users do not experience obvious and unacceptable interruptions during the handoff. Example of such a solution is the FMIPv6[28].

The FMIPv6 approach uses information from Layer 2 to speed up the handoff process. FMIPv6 aims to reduce the handoff delays for mobile connections by anticipating their IP layer mobility and discovering the new router prefix before being disconnected from the current router.

2.6 Topology Control

The network topology in WSNs could be changed dynamically due to the user mobility or due to node faults like battery degradation. In general, topology control is responsible to determine how the nodes are connected so that to form a network topology that optimizes the energy consumption, the capacity of the network, reduces signal interference and at the same time retain the connectivity. Due to the fact that mobile node position is changed frequently, the topology control must be
able to act quickly so that to retain the connectivity. On the other hand, topology control must be able to support the connectivity of the MN by providing new attachment points to the MN.

Topology construction can be classified based on the way that the topology is built. One category of topology construction algorithms is the category where there is a control of transmission range (CTR) of the sensor nodes. Another category is the topology construction algorithm of specific topologies like tree topologies. The distinguish between those categories does not mean that approaches from those categories are mutually exclusive. For example, building a hierarchical topology can be done controlling the transmission power of the sensor nodes. Some techniques consider that nodes have information about their own positions and their neighbours or that they have directional antennas. Another approach is to turn unnecessary nodes off while preserving important network properties (Connected Dominating Set (CDS) paradigm).

We can classify the CTR algorithms as homogeneous and non-homogeneous. In the first case, all sensor nodes in the network are using the same transmission power while in second case different transmission powers at the sensors nodes are assumed. In addition, there is a separation in centralized and distributed homogeneous and non-homogeneous algorithms. In centralized homogeneous algorithms the goal is to find the minimum homogeneous transmission range (CRT) that, applied to every node, and will produce a connected graph. Two solutions of finding the CRT are the Euclidean Minimal Spanning Tree, EMST, that will provide the minimal
cost coverage of all nodes in the graph and the Geometric Random Graphs that analytically produces, with high probability, a connected topology under some assumptions. The disadvantages of the EMST solution are that the exact position of the node is required, and it is very expensive in terms of energy and overhead. The second solution it only applies to dense networks and it is not very accurate.

In centralized non-homogeneous algorithms the goal is to find the maximum power level per sensor node so that to produce a reduced strongly connected graph. This approach, is well-known as the Range Assignment (RA) problem. A disadvantage of this approach is that in case of two or more-dimensional network the solution of the RA problem in NP-hard. In addition, another one disadvantage poses because of the different transmission ranges of the sensor nodes and the possibility to have unidirectional links. The use of centralized topology control approach assumes a central entity (ex. Sink node) that has fully knowledge of the network and decides the optimal topology. A more realistic approach is given by distributed algorithms that in contrary to the optimal topology that the centralized algorithms produce, they construct ”reasonable good quality” topologies. The distributed algorithms can be classified to location-based, direction-based, neighbour-based and routing-based. In location based every sensor node assumes that every node knows its own position. The two most-known location-based algorithms are the RM [29] and the LMST [30] protocols. In the direction-based techniques the nodes are able to determine the relative direction of the signals received from their neighbours. Example of direction-based protocols are the CBTC [31] and the DistRNG [32] protocols. In
the neighbour-based nodes only need to have the ability to determine the number of neighbors inside the maximum transmitting range change and calculate a neighbour set based on the distance between nodes or link quality. The target of this protocols is to create a connected topology using the smallest necessary set of neighbours, and the minimum transmission power possible. Example of protocols in this category is the K-Neigh [33] and the XTC [34] protocols. The routing-based techniques rely on the idea that all the nodes that are included in the routing table of a node are reachable, therefore the transmission range does not need to be adjusted. Example of routing based technique is COMPOW [35] protocol. In addition, another category of topology control mechanisms is the hierarchical-based topology construction mechanisms that can be classified as backbone-based, adaptive, and cluster-based. In this category, a communication hierarchy is created in which a reduced subset of the nodes is selected and given more responsibilities on behalf of a simplified and reduced functionality for the majority of the sensor nodes. An example of a distributed implementation for growing a tree of hierarchical backbone-based algorithm is the A3 [36] protocol.

2.7 Handoff in Wireless Networks

In mobile wireless networks (mainly cellular networks) the handoff is the process where the mobile user maintains its active connection when it moves from the coverage of one access point to another in order to achieve continuous service. In
literature, different types of handoffs are presented. We two well known categories are the horizontal versus vertical handoffs and the hard versus soft handoffs.

2.7.1 Horizontal versus Vertical handoffs

Horizontal handoffs in a cellular networks occurs between the same networks and can be broadly classified into intracell and intercell handoffs. Intracell handoffs occur when a user, moving within a cell, changes radio channels in order to minimize the interference under the same base station. Instead, intercell handoffs occur when an mobile user moves into an adjacent cell and, therefore, all the connections should be transferred to the new base station. Vertical handoff is the process of changing the mobile active connection between different wireless technologies. Vertical handoffs can be further distinguished into upward versus downward and to imperative versus alternative. An upward vertical handoff occurs from a network with small coverage and high data rate to a network with wider coverage and lower date rate. On the other hand, a downward vertical handoff occurs in the opposite direction. Imperative handoff occurs due to technological reasons only. This could be based on parameters such as signal strength, coverage, and the QoS offered by the new network. These handoffs are imperative because there may be a severe loss of performance or loss of connection in case they are not performed. On the other hand, the alternative handoff occurs due to reasons other than technical issues [37]. The factors for performing an alternative handover include a preference for a given network based on price or incentives. User preferences based on features or promotions as well as
contextual issues might also cause handover. Finally there may be other network services that are being offered by certain networks.

### 2.7.2 Hard versus Soft Handoffs

In case of the hard handoff the connection to the current cell is broken, and then the connection to the new cell is made. This is known as a “break-before-make” handoff. On the other hand, in the soft handoff the connection is made to the new cell before leaving the current cell. This is known as a “make-before-break”. Soft handoff requires less power, which reduces interference and increases capacity. A special case of soft handoff exist, named softer handoff where the radio links, that are added and removed from a connection, belong to the same base station. The main advantage of soft handoffs resides on the fact that a call could only fail if all of the channels are interfered or fade at the same time. Thus, in case of soft handoff the reliability is increased compared to the hard handoff. Despite that, due to the fact that soft handoffs have multiple simultaneously connected channels, the hard handoff is cheaper because it requires only one channel to operate.

### 2.7.3 Network versus Node Assisted Handoffs

In the case of Mobile-Controlled handoff, the MN is continuously scanning the wireless medium in order to monitor the signals of the surrounding available base stations and the interference levels on all channels. The handoff is initiated if the signal strength of the serving base station is below a threshold. In contrast, in the case of the Network-Controlled Handoff, the surrounding base stations measure the
signal from the mobile node. The network triggers the handoff procedure, if the
handoff criteria are met, for example the level of SIR is above or below a predefined
threshold. Finally, in the case of the mobile assisted handoff the network requests
from the mobile node to measure the signal from the surrounding base stations. The
network makes the handoff decision based on reports received from the mobile node.

2.7.4 Handoff Process

The basic handover process consists of three main phases. These are the meas-
urement phase, the decision phase, and the execution phase.

The measurement phase is responsible to initiate/trigger the handoff procedure.
In this phase several measurements are carried out like the Received Signal Strength
(RSS), the Signal to Interference Ratio (SIR), the distance measure, and the Bit
Error Rate (BER). Based on the measurements we decide whether a handoff is
needed and if so, to initiate the process. Several methods for handoff initiation may
be found in [38].

The handover decision phase involves the selection of the target point of attach-
ment and the time of the handover. This phase consists of the assessment of the
overall QoS of the connection and its comparison with the requested QoS attributes
and estimates measured from the neighboring cells. Depending on the outcome of
this comparison, the handover procedure may or may not be triggered.
Finally, during execution phase the connections need to be re-routed from the existing network to the new network in a seamless manner. This phase also includes the authentication and authorization, and the transfer of user’s context information.

2.8 Fuzzy Logic-based Systems

During the past decade, fuzzy logic control has emerged as one of the most active and fruitful research areas in the application of fuzzy set theory, fuzzy logic and fuzzy reasoning. Fuzzy set theory is a generalization of normal set theory and was introduced by Zadeh in 1965 [39]. It is one of the family of tools of what is commonly known as Computational Intelligence (CI). CI is an area of fundamental and applied research involving numerical information processing. In normal set theory, an object is either a member of a set or not and the set is often referred to as a crisp set. On the other hand, fuzzy sets have degrees of membership to that set; therefore, it is possible for an object to have partial membership in a set. This forms the basis of fuzzy-set theory. The capability to qualitatively capture the attributes of a control system based on observable phenomena is a main feature of fuzzy logic control and has been demonstrated in various research literature and commercial products. The main idea is that, if the fuzzy logic control is designed with a good (intuitive) understanding of the system to be controlled, the limitations due to the complexity system’s parameters introduced on a mathematical model can be avoided.
Fuzzy Logic Control (FLC) denotes the field in which fuzzy set theory and fuzzy inference are used to derive control laws. Figure 11 presents the general architecture of a FLC system.

The basic idea behind fuzzy logic control is to incorporate the “expert experience” of a human operator in the design of a controller in controlling a process whose input-output relationship is described by a collection of fuzzy control rules (e.g. IF-THEN rules) involving linguistic variables. The input variables in a fuzzy control system are generally mapped into “fuzzy sets”. The process of converting a crisp input value to a fuzzy value is called “fuzzification”, where defuzzification is a mapping from a space of fuzzy control actions defined over an output universe of discourse into a space of non-fuzzy (crisp) control action. A fuzzy set is defined by a membership function that can be any real number in the interval [0, 1], expressing the grade of membership in which an element belongs to in that fuzzy set.

Usually, a fuzzy controller design is based on empirical methods, a methodical approach of trial-and-error. This method is considered to be simple in terms
of design and implementation. Thus, concerning the limitations which arise from sensor networks, this method seems to be a suitable approach for our system. In order to achieve the desired performance, the membership functions were defined based on the real data obtained from long-term testbed evaluation and based on the characteristics of the underlying system.

The general procedure that was followed consists of the following steps:

- Step 1: identify input and output variables.
- Step 2: determine fuzzy sets for the input and output linguistic variables.
- Step 3: choose the membership functions for the input and output fuzzy variables and derive the fuzzy control rules.
- Step 4: define inference engine.
- Step 5: choose the right defuzzification method.
- Step 6: run the simulation of the system and analyze the performance. If needed, perform tuning of the membership functions and then test the system again.

FLC has been successfully applied in controlling numerous systems where analytical models are not easily obtainable or the model itself, if available, is too complex and possibly highly non-linear (e.g. in communication networks). FLC concentrates on attaining an intuitive understanding of the way to control the process, incorporating human reasoning in the control algorithm. It is independent of mathematical
models of the system to be controlled. In addition, one of the key advantages of using the Fuzzy logic is the fact that it handles multiple inputs. It achieves inherent robustness and reduces design complexity. This is in contrast with conventional control approaches that concentrate on constructing a controller with the aid of an analytical system model that in many cases is overly complex, uncertain, and sensitive to noise.

Some research works [40] [41] propose the use of heuristic models, like fuzzy logic, to support the handoff triggering decision. In [41] authors provide a fuzzy logic system to support the mobility procedure based on the RSSI level, the velocity of the mobile node, the number of hops to the sink node, and some other metrics such as traffic load, energy level, and link quality value. Even though the proposed solution was discussed in detail, there was no implementation or evaluation of it. Therefore, the applicability of the solution and any possible overhead are undetermined. In addition, the high number of metrics that they aim to use will, undoubtedly, lead to an increased complexity of the fuzzy logic system, since a big number of rules must be enabled at any time. Due to the limited capabilities of the sensor nodes a fuzzy logic-based system must be as simple as possible.

Several works using fuzzy logic techniques have appeared in the field of mobility management, with the majority targeting the support of vertical handoffs. In [40], a handoff decision for heterogeneous networks is identified as a fuzzy multiple attribute decision-making problem and fuzzy logic is applied to deal with the imprecise information. In [42], a handover algorithm is proposed to support vertical handovers.
between heterogeneous networks. This is achieved by incorporating the mobile IP principles in combination with fuzzy logic concepts utilizing different handover parameters. Furthermore, in [43], the authors deal with a vertical handover decision algorithm based on the fuzzy control theory. The algorithm takes into consider the factors of power level, cost, and bandwidth in order to decide about the vertical handover. In [44] [45], the authors proposed and implemented a Fuzzy-Based Handover System (FBHS), where they showed that the proposed system had a good behaviour for handover enforcement, but in some cases could not avoid the ping-pong effect.

In this work, we propose a fuzzy-based solution that does not change the existing conventional algorithms, but uses operations of them in order to provide a system that will manage to control the handoff procedure and provide improved performance.
Chapter 3

Industrial WSN System Architecture

The growth of wireless sensor networks utilization has generated research attention in systems that need to provide certain performance assurances. Nowadays, there is also an increased interest from industrial operations to use sensor networks, due to the low deployment and maintenance cost that they can provide. Industrial production plants such as oil refineries, chemical plants, or waste water treatment plants are using wired sensor systems to monitor and control their production processes. As the deployment and maintenance of such cabled systems are expensive it is desirable to replace or augment these systems using wireless technology. Wireless sensing can be used to provide solutions in the industry for leakage detection, climate reporting, radiation check, intrusion notification, production monitoring and actuation, safety and worker healthcare monitoring, and material and equipment tracking. Using WSNs, the significant drawbacks of wired systems like the deployment and reconfiguration can be addressed.
3.1 Communication Standards

3.1.1 IEEE 802.15.4 Standard

IEEE 802.15.4 is the proposed standard for low rate wireless personal area networks. It operates in 3 bands as shown in Table 1 ([51]). The features of the layer are activation and deactivation of the radio transceiver, energy detection within the current channel, link quality indication for received packets, channel selection, clear channel assessment (CCA), and transmitting as well as receiving packets across the physical medium. IEEE 802.15.4 is designed for wireless sensor applications requiring short range communication to maximize battery life.

Table 1: 802.15.4 Physical layer

<table>
<thead>
<tr>
<th>Frequency(Mhz)</th>
<th>Modulation</th>
<th>No of channels</th>
<th>Bit rate(Kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>868-868.6</td>
<td>BPSK</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>902-928</td>
<td>BPSK</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>2400-2483.5</td>
<td>16-ary QPSK</td>
<td>16</td>
<td>250</td>
</tr>
</tbody>
</table>

3.1.2 Standards based on IEEE 802.15.4

1. ZigBee[52][53] technology is a low data rate, low power consumption, low cost, wireless networking protocol targeted towards automation and remote control applications. IEEE 802.15.4 committee started working on a low data rate standard a short while later. Then the ZigBee Alliance and the IEEE decided to join forces and ZigBee is the commercial name for this technology. ZigBee is focused on radio-frequency (RF) applications that require a low data rate, long battery life, and secure networking. ZigBee has been developed to meet the growing demand for capable wireless networking between numerous low-power
devices. In the industry, ZigBee is being used for next generation automated manufacturing, with small transmitters in every device on the floor, allowing for communication between devices to a central computer.

2. WirelessHART [6] is a standard based on IEEE 802.15.4, for low power 2.4 GHz operation, expecting a huge need for wireless instrumentation. WirelessHART is compatible with all existing devices, tools, and systems. WirelessHART is reliable, secure, and energy efficient. It supports mesh networking, channel hopping, and time-synchronized messaging. Network communication is secure with encryption, verification, authentication, and key management. Power management options enable the wireless devices to be more energy efficient. WirelessHART is designed to support mesh, star, and combined network topologies.

3. 6LowPan [54] is an adaptation layer allowing efficient IPv6 communication over IEEE 802.15.4. It defines a LoWPAN frame format for IPv6 data packets and a simple header compression scheme which uses shared context information. Also, packet delivery in meshes is briefly addressed.

3.2 Industrial Standards

In recent years, several standards for wireless industrial sensor network (WISN) monitoring and control systems have been proposed. The most well known is WirelessHART [6], a wireless extension of the HART standard for interconnection of digital sensor devices. Although it provides several functionalities, no support is
made available for mobile users. The only provision is for WirelessHART enabled handheld devices to enter the network and interact with directly adjacent nodes for calibration checks or direct access to sensor measurements. Nodes in a WirelessHART environment are not expected to be mobile in the sense that they will change their links and neighbours. Other standards include ISA100.11a [7] and IEEE802.15.4e where those systems are generally cast as augmenting wired control systems by allowing them to replace cables with a wireless alternative. No specific mobility management is supported by those standards.

WirelessHART and ISA100.11a use a centralized network management approach for communication scheduling and managing routes. Despite the advantages of such an approach, they perform poorly in situations of highly dynamic changes like the node mobility. This, in turn, may result in problems, including increased packet loss, delayed data delivery, and increased downtime, which increase energy consumption.

Efforts to integrate WSNs with industrial processes using real deployments are embryonic and, especially the support of mobility in such environment, are not supported.

3.2.1 Industrial Mobility Management

Effort in the industrial field usually considers the definition of several applications that use sensors nodes in order to perform a monitoring task. For instance, Salvadori et al [46] describe an application to monitor electrical systems, Merrett
et al [47] describe an application to monitor water-pumping stations, and Ramamurthi et al [48] consider industrial control. Despite that, the applicability of the proposed systems in real environments is not validated. In addition, RACNet [49] is a sensor network that monitors a data center’s environmental conditions. They maintain robust data collection trees rooted at the network’s gateways. The performance results of this work were promising since they have shown a data reliability up to 99% and timely delivery of data. Even though there are some similarities with the objectives of this work concerning the general architecture and the performance issues, like tree topology and high reliability, there is one major difference that distinguishes both works and makes the contribution presented in this thesis unique in the fact that it supports mobile users. EMMON [50] is another system for large-scale, dense, real-time embedded monitoring. EMMON allows a structured network coordination of clusters of nodes, focusing on guaranteeing a given level of QoS. Again, although the requirement of reliable data acquisition is common, EMMON does not target mobile users. Despite the fact that there are several research proposals for wireless sensor network, usage in industrial environments, not many of them are deployed in reality. This is due to the fact that real deployments in industry allowing the evaluation of the applications are difficult to achieve, or they are not continuously available. Therefore, the majority of the researchers evaluate their solutions using simulation tools. The main limitation faced in such evaluations is the mismatch between model and real-life settings. It is common to have an algorithm/system/protocol that works perfectly in a simulation environment, but when
deployed in a real setting it simply fails. One of the main reasons for this failure is the fact that simulations do not utilize representative radio propagation models but they just rely on general theoretical radio propagation models, which may not adequately represent the environment at hand.

3.3 System Setup

This section describes the overall setup and configuration of the system/environment that will be used to evaluate our mobility proposal.

3.3.1 System Architecture

The work presented in this section is based on specific underlying work done in the European project GINSENG [2] whose objective was to create a wireless sensor network that would meet application-specific performance targets and that would be proven in a real industry setting where performance is critical. To achieve this goal, a specific functional architecture was proposed which defined how the different modules should collaborate in order to have a system that could accomplish the required performance. The end user of the GINSENG project was the Petrogal oil refinery at Sines. The Petrogal refinery is a complex industrial facility consisting of a wide range of processing that needs careful monitoring and control of operations. The monitoring of the environment in a refinery provides essential information to ensure the good health of the refinery and its production processes. In the oil refinery three subsystems exist for the monitoring and control of the plant [55]: the indicator
system, the semi-automatic control system, and the automatic control system. Five types of scenarios were included in the project. These scenarios are: Production Monitoring, Production Control, Production Monitoring and Control, Pipeline Leak Detection and Personnel Safety. The Personnel safety scenario requires the use of mobile nodes and is the scenario used for the requirements extraction, development and evaluation of our mobility solution.

As mentioned, the general target is to develop mobility solutions that could provide controlled performance in Wireless Sensor Network. For a network to exhibit deterministic behaviour, every layer from the application to the hardware/physical layers must act in a predictable manner. To achieve this goal, a set of control mechanisms was used in order to ensure deterministic behaviour and to allow the network to meet the application’s specific performance targets. The overall functional architecture is shown in Figure 12.

![Figure 12: System Architecture](image)

The main characteristics of the architecture are:
1. Use of a TDMA-based MAC [56] protocol, called GinMAC.

2. The network uses multi-hop communication through a tree-based topology (Figure 13). The tree consists of H layers, where H is equal to the number of hops from the sink. A reasonable small number of nodes ($N < 30$) is used where $N$ is directly proportional to the required communications delay bound; the smaller the required delay, the smaller the $N$.

![Figure 13: 3-2-1 Tree Topology](image)

3. Use of Dynamic Topology Control (DTC) [57] techniques.

4. The network is made up of resource constrained embedded systems where the majority of the nodes are deployed in fixed and predetermined positions.

5. The majority of nodes are static with no mobility; there are however cases where nodes appear to be mobile by switching positions in the tree when capacity is available.
6. Mobile nodes cannot communicate directly with sink nodes except in the case when they are directly connected to the sink. Thus, the data communication of mobile nodes with the sink is accomplished via the other sensor nodes.

7. Nodes report data frequently at a relatively high rate (up to one per second) and data must reach the sink within a given time bound $T_s$.

For the purpose of this thesis, two modules were designed and implemented: the mobility and the Dynamic Topology control modules.

### 3.3.1.1 GinMAC

As mentioned above, the MAC protocol used as the underlying mechanism is a TDMA-based protocol developed in the context of the EU FP7 project GINSENG [2]. GinMAC assumes that data is forwarded hop-by-hop towards a sink within a tree topology consisting of $n$ nodes. The time axis is divided into fixed-length base units called *epochs*. Each epoch $E_i$ is subdivided into $k \times n$ time slots for a network of at most $n$ sensor nodes. Each node is assigned $k$ exclusive slots per epoch $E$ (sufficient to successfully forward messages from the node and its children in one epoch). The slots at each epoch are divided to active, idle and processing. The active slots can be slots for transmission, and for reception. A special case of reception slots are the scanning slots were the node can receive any packet transmitted by any node in its communication range. In addition, since slots can be used to communicate between parent and child nodes, we can characterized them as downstream (from parent to child) and upstream (child to parent) slots. A network dimensioning process is
carried out before the network is deployed. The inputs for the dimensioning process are the network and application characteristics, which are known before deployment. The output of the dimensioning process is a TDMA schedule with frame length $F$ that each node has to follow. As a TDMA protocol, time synchronization is necessary. For this purpose, a node listens every $k$ frames in the first slot that its parent node transmits data upstream. Thus, all nodes synchronize their time with the sink. Every node must always transmit a packet in the first slot used for upstream data, sending a ”dummy” packet (a packet without payload) if no data is available. The packet header contains information on how many packets the sender has to transmit in the current frame.

3.3.1.2 Proposed Dynamic Topology Control (DTC) Model

The goal of the proposed dynamic topology control is to connect all nodes in the network and organize them in a tree structure topology to serve the needs of the MAC protocol. In our work, we do not assume any central entity that has full knowledge of the network and will be responsible for constructing the topology. The decision is made locally by each sensor node. The topology is constructed in a distributed manner while the nodes use the same transmission power during the construction phase.

We can describe our basic topology control algorithm as a distributed homogeneous algorithm that produces a tree topology based on good links. Figure 13 presents an example of a supported tree with the structure of 3-2-1 able to support
16 nodes (including the sink). Different tree structures, in terms of number of levels and children per level, can be used in order to support any number of nodes. Regarding the topology construction, we use MAC signalling (control messages) in order to discover our neighbours. The discovery of the neighbour nodes (parent and children) is done by the exchange of advertisement control messages (ADVERT). The first node that starts sending advertisement messages is the sink node.

The advertisements are broadcast messages that advertise specific children tree positions. The advertisements are sent in the downstream slot of the epoch. When a node (not the sink) is firstly switched on it initializes during the first epoch and...
sets all the slots of the node in ”scan mode” so that to receive advertisements. Upon receiving an advertisement, the MAC will pass this packet to the topology control module running in each node, which will process the packet and select randomly a tree address to be attached. Then, the node will send a JOIN control packet to the advertiser node asking a confirmation to use the specific tree address. In case that a new node receives more than one advertisements it will select to join in the address with the best RSSI value and closest to the sink node (minimum number of hops from the sink). In the case that two different nodes select to join at the same tree address there will be a collision and the nodes will back-off and select a tree address again in the next epoch. Upon accepting a join request, the parent node will create a join acknowledgement packet (JOIN_ACK) and send it to the child node. A child node receiving the join acknowledgement changes its status to attached and starts sending data upstream as well as advertising its children positions (if any). If the node is a leaf node it can not support child positions thus it is not sending advertisement. In order to keep track of the node state each node maintains a list where it keeps information about its children and free position(s). If the node does not receive any advertisements during its initialization phase it sets all the slots in idle mode and wakes up after a predefined time to listen for advertisement messages and repeat the above procedure. Figure 14 depicts the messages exchanged during the construction phase of the proposed topology control.

We can characterize the tree nodes with their decoded addresses. For example 3-0-0 is the decoded address where it means that is the third child of the sink node.
The scanning slots in DTC and mobility modules are used to discover the neighbouring nodes and therefore to construct and maintain the tree topology. This is achieved by the fact that when the node sets its mode to scanning, it can receive any packet from any node inside its communication range. Therefore, the MN will know with which nodes it can directly communicate. Despite the importance of scanning slots, their number must be kept to low values since they affect the total power consumption. Thus, in case a node sets its idle slots to scanning mode for a long period it will exponentially increase the power consumption and therefore it will reduce the lifetime of the sensor node.

**Tree Construction Delay:** In order for one node to be attached to the parent node three messages must be exchanged: ADVERT, JOIN, JOIN_ACK. The time to transmit the messages is strongly dependent on the MAC frame size. The time duration of this frame is called epoch. The duration of the epoch is depended on the tree structure. The MAC frame is consisted of a number of slots with two directions: upstream and downstream. In our case upstream slots are used to send the JOIN request messages while downstream slots are used to send the ADVERT and the JOIN ACK messages. The upstream slots are located first inside the MAC frame and the downstream slots at the end of it. More details about how the MAC frame is constructed can be found in [56].

To calculate the best-case tree construction time we have to consider the $E$: epoch duration, the $L$: layer level, the $H$ is the three depth, the $M$: required number of control messages, and $S$: synchronization delay.
Tree Construction Time:

\[ S + \sum_{L=1}^{H} E \times L \times M \]  

(1)

3.3.2 Network architecture

The testbed network architecture is comprised of three kinds of nodes: Sink Node (SinkN), Static Node (SN) and Mobile Node (MN). Each type of node is characterized by a different role in the network, and different capabilities in terms of energy, communication and mobility.

- A SinkN represents the final destination of the information generated by the WSN. Sink node is responsible for using DTC to start the procedure of constructing the tree. The sink is located to the portable office and it is connected directly to the sink PC where the Dispatcher and the Monitor applications are also located. The Dispatcher records all data coming from the WSN to XML files and also enables multiple consumers (such as the middleware or the performance monitoring) to receive the information in different formats. The sink is a fixed node and there is no limitation on energy since it is powered from the USB connection with the sink PC.

- The SNs are fixed nodes that are installed in pre-defined positions in such a way to measure the appropriate values (pressure, flow, temperature, etc) which the application requires. The SNs can be main-powered or battery-powered.
• The MN is carried by the mobile user in an ATEX case (with an external antenna) in its backpack. MN is powered with batteries, therefore energy consumption is important.

3.3.3 Mobility Scenario

Mobility support in this work has been mainly related to monitoring mobile workers. There are many hazardous activities in the plant which need to be monitored for safety. One such activity is the cleaning and condition assessment of storage tanks. Tanks are very hazardous environments and typically contain a toxic atmosphere and residues of their previous contents. When employees enter such hazardous areas there is the possibility of losing consciousness. By using orientation and heart or pressure monitoring sensors attached to employees, their condition can be monitored and alarms can be signalled when an emergency occurs. This scenario is a specialized case of the indicatory system which includes nodes that are mobile. Figure 15 depicts this application scenario. Surrounding the tank that is being cleaned are usual sensors deployed for other scenarios, e.g. production monitoring. As the mobile worker moves around the tank, orientation messages are sent from the sensor to the sink forwarded by intermediate nodes. Data may be sent via different intermediate nodes based on the location of the mobile worker. The orientation of the mobile worker is monitored by trip sensors. This enables fallen/unconscious workers to be detected. Orientation is sampled at a frequency of 0.2Hz.
In order to continuously receive information from the mobile workers, a mobility management protocol must be implemented so as to enable the handoff between different access points. For example, based on Figure 15, we have three possible receiver nodes (indicated by the numbers 1, 2 and 3). The mobile worker at the beginning of his trip is attached to the receiver node 1. When the mobile worker is near to receiver node 2, the communication link with receiver node 1 is still good, therefore there is no need to handoff. However, as the mobile node is far away from receiver node 1, it has to handoff to a new position. Possible new connections points are receiver nodes 2 and 3, but based on the communication quality the mobile worker will prefer to connect with receiver node 3.

In terms of the plant network, these mobile workers are temporary objects that only exist for a short period of time (time it takes to complete a specific job). Similarly to other scenarios, information must arrive at the control centre within few seconds. Although packet losses should be minimized, this application can be
tolerant to a small amount of loss. Table 2 summarizes the mobility requirements for Personnel Safety scenario.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay</td>
<td>The Time bound of data delivery</td>
<td>Data should arrive at the in-field sink in 1 second.</td>
</tr>
<tr>
<td>Reliability</td>
<td>How important is data delivery</td>
<td>&gt;97%</td>
</tr>
<tr>
<td>Mobility</td>
<td>Level of Mobility</td>
<td>Mobile Workers</td>
</tr>
<tr>
<td>Network Size</td>
<td>Maximum number of Nodes</td>
<td>30</td>
</tr>
<tr>
<td>Topology Classification</td>
<td>Type of Topology</td>
<td>Tree</td>
</tr>
<tr>
<td>Hop Count</td>
<td>Max Number of Hops nodes can reside from the sink</td>
<td>4</td>
</tr>
<tr>
<td>On Node Processing</td>
<td>Level of on node processing</td>
<td>Filtering of data to report.</td>
</tr>
<tr>
<td>Traffic Classification</td>
<td>Is all traffic time-critical, none time critical or mixed</td>
<td>Mixed</td>
</tr>
<tr>
<td>Traffic Characteristics</td>
<td>Type of Traffic</td>
<td>Periodic upstream, adhoc downstream.</td>
</tr>
<tr>
<td>Time Critical Traffic Direction</td>
<td>What direction are the time-critical flows in?</td>
<td>Upstream</td>
</tr>
<tr>
<td>Non-Time Critical Traffic Direction</td>
<td>What direction are the non time-critical flows in?</td>
<td>Downstream</td>
</tr>
<tr>
<td>Number of Time Critical Flows</td>
<td>How many time-critical traffic flows are there?</td>
<td>One per node upstream.</td>
</tr>
<tr>
<td>Traffic Characteristics</td>
<td>Type of Traffic</td>
<td>Periodic</td>
</tr>
<tr>
<td>Traffic Frequency</td>
<td>How often does each node generate a packet</td>
<td>&gt; 1 seconds</td>
</tr>
<tr>
<td>Traffic Delay Bound</td>
<td>Time bound of the time-critical traffic</td>
<td>Upstream 1 seconds</td>
</tr>
<tr>
<td>Number of mobile nodes</td>
<td>The total number of mobile nodes used in our tests</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3.4 Learning the environment

Industrial environments perform in an unpredictable way due to specific radio propagation characteristics, like rapid fluctuations and reflections of the propagation
signal. In addition, the dynamically changing physical environment, possibly due to moving objects like trucks, fork-lifts, etc poses some unique challenges in terms of the mobility management solution. Thus, some actions, like investigation of the refinery environment characteristics, had to be performed prior to proposing a mobility solution.

To do so, we first run some initial tests in order to extract the characteristics of our testbed environment. We used a TelosB sensor node that was configured to run the baseline architecture setting enhanced with DTC functionalities and we performed different walks in the refinery area following possible paths where refinery workers would work. The results clearly show that, indeed, there is a need for mobility management. Specifically, we performed a 20-minutes walks inside the refinery area, and we measured an average packet loss to be equal to 9.05%, which is a value that does not correspond to our performance requirements. In addition, a realization of the above-mentioned tests was that, as the refinery has a lot of metal structures and high voltage motors, the antenna that is to be connected to the mobile node must be powerful enough to transmit between nodes. To do so, a 9dB antenna was selected. Furthermore, since there is no channel hopping provision in the system architecture, a spectrum analysis must be performed so as to find the communication channel with the minimum noise. Finally, it was clear that, based on the static nodes deployment, there are always small areas where the communication will not be feasible (black areas). Adding some relay nodes could help to minimise those black areas.
As performance metrics like the packet loss and RSSI are very critical for the successful operation of our solution, we ran some tests with the aim to achieve a relation between the packet reception rate (PRR) and RSSI. The goal was to see if we could ascertain a relationship between the two, thus assuring a certain percentage of packet delivery at a certain RSSI threshold. In our case, our critical application required a PRR of 0.99 so, based on Figure 16 which compares the PRR values with the associate RSSI, we chose the RSSI threshold to be equal with -78 dBm.

![Figure 16: End-to-End loss vs RSSI](image)

**3.4 Radio Propagation model**

In recent years, sensor networks characteristics have led to incremental utilization in different types of applications. Several techniques have been proposed to evaluate the performance of WSNs; the two most popular being mathematical analysis and simulations. An important drawback of these techniques is that they provide
evaluation results which usually are not similar to those of real deployments. One reason for this is the fact that both techniques introduce physical layer modelling assumptions, which do not usually correspond to real-life environments.

Several radio propagation models have been proposed in the literature and are used in mathematical and other analyses. The main way to categorize those models is on the distance separating the transmitter and the receiver. The two main categories are the large-scale propagation models, which predict the average received signal strength over large distances (hundreds of meters or kilometers) and the small-scale propagation models where the distance between transmitter and receiver is of some meters. The small-scale propagation models target to characterize the fluctuations of the received signal in greater granularity. Figure 17 shows our view of taxonomy for the propagation models.

![Figure 17: Radio Model Taxonomy](image-url)
In addition, propagation models can be classified into theoretical and empirical. Both theoretical and empirical-based models indicate that signal decreases logarithmically according to distance. The most known theoretical propagation model is the free-space propagation model and is used to predict the received signal strength when the sender and receiver have clear line-of-sight. In the free space model the received signal strength falls off proportionally to the distance. The assumption of a non-obstacle environment makes the free-space model unrealistic. A theoretical model named 2-Ray Ground Reflection is also used, which considers both a direct path and a ground reflected path between sender and receiver. The 2-Ray Ground model provides accurate prediction over distances of several kilometers.

On the other hand, a more complex model is the log-normal shadowing radio propagation [58] where the received signal strength does not depend only on the distance between transmitter and receiver, but also includes a zero-mean Gaussian distributed random variable that accounts for the attenuation caused by buildings or any obstacles between a sender and a receiver. An advantage of the log-normal shadowing radio propagation model over the two aforementioned models is the fact that it considers an imperfect environment without obstacles.

The most well known empirical model is Hata’s model [59] which is an empirical formulation of the Okumura model [60] and is considered to provide the best accuracy in path loss prediction for cellular and mobile system environments. The Hata model is considered to work best in urban and sub-urban areas but the main
drawback of this model is that it cannot respond to changes in terrain, therefore it is not suitable for rural areas.

In the case of small-scale models, fading is the most observed phenomenon. Fading is the deviation of the attenuation affecting a signal over certain propagation media and it can happen due to shadowing, called slow-fading or due to interference among signals propagating over many paths to the receiver, called fast-fading. An example of a model capturing the slow-fading is the log-normal model, while Rician and Rayleigh distributions are often used for fast-fading models.

### 3.4.1 Refinery Radio Propagation Model

In this section, we will use measurements obtained from a prolonged campaign in the oil refinery to propose a new radio propagation model for use in simulations. The proposed radio model will be validated by matching the performance of the simulated network to that of the real network, both in conditions involving static nodes and those in which mobile nodes were also present.

It is clear that COOJA can be used to evaluate and compare the behaviour of the different mobility solutions but, as mentioned above, without considering the refinery radio propagation model, it will fail to give values that correspond to the testbed evaluation results. This drawback was the motivation to further investigate the radio propagation model of the refinery environment. The analysis of the refinery radio propagation and proposal of a radio propagation model, that
will be implemented and used in COOJA simulator, will help us to minimize the
gap between real-life evaluation results and simulation results.

The refinery is a multifaceted industrial facility that includes a wide range of
processing units that need careful monitoring and control of operations. The refinery
environment is unpredictable with high levels of electromagnetic interference and
with metal structures and pipes acting as obstacles to radio communication. This is
something that makes any similar modelling endeavor extremely difficult, but also
highly important.

3.4.2 Radio Measurements

Using the functionalities of a Dynamic Topology Control module, we constructed
several trees so that to obtain as many different links with different distances and
obstacles as possible. Using the 3D Euclidean distance formula, we calculated the
distance between all the possible links. Since our testbed consisted of 13 nodes, there
are 156 possible links but due to the difficult environment (a lot of obstacles and
metal constructions) not all the communication links were possible. We managed
to obtain 132 different link observations. Based on our calculations the maximum
distance between nodes in our network is 29 meters. Therefore, we can characterize
our model as a small-scale propagation model.

Modelling the environment as having a log-normal loss we obtained Equation 2:

\[ RSSI = -10 \beta \log\left(\frac{d}{d_0}\right) + X_{dB} \] (2)
Figure 18: Comparison with theoretical values of free-space and fading models

where $X_{dB}$ is a Gaussian random variable with zero mean and standard deviation $\sigma_{dB}$. At a first stage we used [58] and we set the value of $\sigma_{dB}$ to be equal to 6.8.

Figure 18 shows the relationship between the distance, the obtained RSSI values in the refinery environment and the theoretical radio propagation models. In case of the log-normal model we show the ranges of the possible values using the upper and lower possible limits given the $X_{dB}$ value. It is obvious that the obtained values correspond neither to the log-normal model nor to the free space model. Consequently, we decided to proceed with further investigation of the refinery model.

To do so, we used the data that we obtained from refinery evaluation and we calculated the $\sigma_{dB}$ to be equal to 12.27 and the $\beta$ to be equal to 5.78.

Figure 19 shows the relationship between the distance, the obtained RSSI values in the refinery environment and the calculated log-normal propagation model. It is
obvious that the calculated log-normal model shows an improved match with the refinery values. Despite that, we observe some anomalies to the plotted lines which means that same distances provide different RSSI values.

In addition to the instantaneous obtained values, we observed the variation of the RSSI value of each link. The experiments were run for a long time (11 days). Except the average values per distance, we also measured the variation of the RSSI per node. Since our network architecture is consisted of static and MN, we wanted to understand how the RSSI changes for different types of nodes. Therefore, we observed that for the static nodes the sigma value between the obtained signal was 0.65, whereas in the case of the mobile nodes the sigma value was 4.85. It is obvious, as expected, that the mobility of the node affects the received signal strength. We have not yet managed to provide a correlation between specific mobility models and measured signal strength values, since this is part of an on-going investigation.

Figure 19: Log-normal model based on refinery data
This fact, however, does not deter us from our ability to characterize correctly the environment for static and limited-mobility nodes.

3.4.3 RSSI Statistical Analysis

The data consist of 132 observations whose summary statistics are given as follows:

Table 3: Statistics Summary

<table>
<thead>
<tr>
<th>Min</th>
<th>1st Q</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Q</th>
<th>Max</th>
<th>St.Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90</td>
<td>-64.25</td>
<td>-57.50</td>
<td>-57.34</td>
<td>-48.75</td>
<td>-27.00</td>
<td>12.27</td>
</tr>
</tbody>
</table>

Exploratory statistical analysis shows that the distribution of the data exhibits reasonable symmetry (indicated also by the fact that the sample mean and sample median are very close to each other). The histogram, boxplot and density of the data indicate that, indeed, the distribution of the values is symmetric (Figure 20). In addition, the normal qqplot (quantile-quantile plot), i.e., the plot of the ordered values of the data versus the corresponding quantiles of the standard normal distribution is fairly linear, indicating that the data are reasonably Gaussian.

The assumption of normality is further substantiated by comparing the empirical distribution function of the data with the theoretical normal distribution function. The two distribution functions are very close to each other, as can be seen in Figure 21.

The visual findings of the exploratory statistical analysis can be verified by means of statistical tests. Two statistical tests, the chi-square goodness of fit test and the one sample Kolmogorov-Smirnov test for testing composite normality, both verify
Figure 20: Histogram, boxplot, density and quantile-quantile plot of the data that, indeed, the data are normally distributed. The chi-square goodness of fit test for testing the null hypothesis that the data are normally distributed versus the alternative that the cumulative distribution function does not equal the normal distribution for at least one sample point gives a p-value of 0.42, and thus, the assumption of normality cannot be rejected at any reasonable level of significance. Similarly, the one sample Kolmogorov-Smirnov test for testing the null hypothesis that the data follow the normal distribution versus the alternative, that the true cumulative distribution function does not equal the normal distribution, produces a p-value of 0.352. As a consequence, the null hypothesis cannot be rejected at any reasonable level of significance. Based on the two statistical tests (which both are considered to be very strict) and the exploratory statistical analysis, it is safe
to conclude that the data are normally distributed. As such, the received signal strength of the refinery radio propagation model is obtained by the following formula:

$$RSSI(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$$  \hspace{1cm} (3)

### 3.4.4 Link Loss Analysis

In addition to analyzing the RSSI behavior, we proceeded with the evaluation of how the RSSI affects the Packet Reception Rate (PRR). Analyzing the refinery testbed logs we extract the relationship shown in Figure 22.

Based on Figure 22 it is clear that we can successfully deliver packets, with negligible packet losses, if the RSSI is above -70dBm. Those losses are slightly increased until -80dBm and beyond where the losses are increased exponentially and the PRR drops significantly. We use a 6th order polynomial formula to fit the data as it is shown in Figure 22. The obtained formula is the following:

$$y = p1 \cdot z^6 + p2 \cdot z^5 + p3 \cdot z^4 + p4 \cdot z^3 + p5 \cdot z^2 + p6 \cdot z + p7$$  \hspace{1cm} (4)
where the coefficients are: $p_1 = -0.011723$, $p_2 = 0.030365$, $p_3 = -0.00043912$, $p_4 = -0.039766$, $p_5 = 0.009391$, $p_6 = 0.015609$, $p_7 = 0.99552$ and the norm of residuals is 0.063323. In addition, in equation 15 $z$ is centered and scaled with $z = (x - \mu)/\sigma$, where $\mu = -60.1$ and $\sigma = 17.753$.

### 3.4.5 Radio Propagation Model Evaluation

Based on the above conclusions, we implemented the new radio propagation model, as a normal distribution function, and we also used Equation 6 to calculate the link loss. The new model was ported to the COOJA simulator and several numbers of tests were performed in order to identify if the new model manages to successfully capture the refinery radio conditions. The first test that we run was to identify if the proposed model statistics (mean and sigma) in COOJA simulations match the real testbed statistics. Table 4 summarizes the simulator obtained values and the testbed values.
Table 4: New model vs testbed results

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Sigma</th>
<th>Sigma next value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation fixed</td>
<td>-58.46</td>
<td>11.77</td>
<td>0.71</td>
</tr>
<tr>
<td>Testbed fixed</td>
<td>-58.17</td>
<td>11.79</td>
<td>0.65</td>
</tr>
<tr>
<td>Simulation mobile</td>
<td>-67.84</td>
<td>11.51</td>
<td>4.74</td>
</tr>
<tr>
<td>Testbed mobile</td>
<td>-70.39</td>
<td>11.22</td>
<td>4.85</td>
</tr>
</tbody>
</table>

It is obvious that based on the arithmetic values we managed to simulate with high accuracy (minimum of 97%) the refinery radio model obtained values using the COOJA simulator. Figures 24, 23, 25, 26 show the behavior of RSSI over the time of both fixed and mobile nodes. Those figures show that the proposed radio model managed to simulate the refinery environment.

![Fixed node: RSSI current - RSSI previous - Testbed](image1)

![Fixed node: RSSI current - RSSI previous - COOJA](image2)

Figure 23: Fixed nodes RSSI values using testbed

Figure 24: Fixed nodes RSSI values using proposed model in COOJA

![Mobile node: RSSI current - RSSI previous - Testbed](image3)

![Mobile node: RSSI current - RSSI previous - COOJA](image4)

Figure 25: Mobile nodes RSSI values using testbed

Figure 26: MN RSSI values using proposed model in COOJA
Chapter 4

Mobility Solutions based on Single Metric

4.1 Introduction

With the convergence of mobile and wireless communications and with the rapid growth in the number of mobile entities, mobility management emerges as one of the most important and challenging problems for wireless mobile communication. Mobility management deals with all actions that must be taken in a network in order to support the movement of mobile users without losing connectivity. When a mobile user is in an active communication then a radio link must be established between the mobile user and the base station. When the mobile user moves to another area the radio link may get disconnected and therefore the communication will end. To deal with this situation, the mobile user must change its attachment point. This process is called handoff. The most important task of a mobility management protocol is to achieve seamless connectivity of the Mobile Node (MN) by controlling the handoff procedure.
In this chapter, we investigate both handoff phases (triggering and decision) in WSNs with performance guarantees. We focus on the choice of single-based parameters and the ways of measuring them (e.g. averaging techniques) in order to support the handoff triggering and decision process. In order to investigate the handoff procedure, we firstly implement and test a hard handoff approach and then we proceed with a no-disruption handoff approach. It is important to note, that we base and evaluate the examined triggering and decision parameters in the context of a specific WSN framework (the GINSENG framework; see Section 3.3) that is able to provide reliable and performance controlled operation [55]. In addition, and in contrast to the emerging standards already mentioned, this framework operates in a decentralized and distributed manner and it has been proven to be able to handle all of the issues raised above.

Before proceeding, it is important to highlight the major contributions of this chapter. These are:

- Examination of the commonly-used Received Signal Strength Indicator (RSSI) based solution in WSNs in order to investigate the best hysteresis margin and to discover the best window size of the Simple Moving Average (SMA) and Exponential Weighted Moving Average (EWMA) extensions;

- Proposal of a new handoff triggering mechanism that is based on local link loss characteristics;

- Mobility triggering and handoff in Industrial WSNs: We give a combination of solutions to support the two main phases of mobility control, the triggering
and the handoff. We use the Received Signal Strength Indicator (RSSI) based solution and the Link-Loss based solution in order to investigate their overall performance;

- Burst Loss Algorithm (BLA) Implementation: We propose a new handoff decision mechanism which is based on burst packets acknowledgements;

- Mobility Evaluation: We evaluate the performance of the triggering and handoff decision solutions in terms of the packet losses and effectiveness of the handoffs considering their possible overhead.

4.2 Related Work

In general, in order to have a handoff between two connection/attachment points, a triggering decision must occur. Handoff triggering is the process of deciding when to request a handoff. In the majority of the related work in WLAN and WSNs ([61][62],[38]) the handoff triggering is based on a single metric, like the Received Signal Strength Indicator (RSSI), the Packet Reception Rate (PRR), and Link Quality Indicator (LQI).

The most commonly used triggering/handoff criteria that are based on the above metrics are the following:

- **Better Metric Value**: the MN selects the attachment point with the better metric value. It can be considered as being a simple solution, but it can

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1Note that in cellular networks the Common Pilot Channel Indicator, CPICH, is used in a similar fashion, as for example in MBMS [63]
cause too many unnecessary handoffs. In the case of wireless sensor networks, it increases the energy consumption since the MN must be always on (it is always triggered) for hearing for new attachment points.

- Threshold: if the current metric value is worse than the threshold the handoff is triggered. When a new attachment point with better metric value is available the MN will handoff. The issue with this metric is the threshold value selection since low threshold may lead to late handoffs while high threshold may lead to early handoffs.

- Better Metric Value with hysteresis: the MN selects the attachment point with a sufficiently better (by a hysteresis margin, $h$) metric value compared to the one of the serving attachment point. Using this technique, the ping-pong phenomenon can be avoided. However, there may be the case where the handoff decision that occurs could be unnecessary since the serving attachment point signal may be strong enough to maintain the connectivity. Such unnecessary handoffs increase the overall power consumption.

- Threshold with hysteresis: if the current metric value is worse than the threshold and a new attachment point, with sufficiently stronger (by a hysteresis margin, $h$) metric value is available, then the MN will handoff. Using this technique, the ping-pong phenomenon can be avoided.

The importance of the RSSI metric as a quality indicator was argued in [64] where the authors have shown that generally for RSSI values greater than -87dBm
the resulting PRR is at least 85%, indicating a very good link. In addition, they have shown that RSSI is a promising indicator when its value is above the sensitivity threshold of the radio communication chips (in their case the CC2420 chip). Finally, they concluded that protocol designers looking for inexpensive and agile link estimators may choose RSSI over the Link Quality Indicator (LQI).

In [65] the authors measure the wireless link burstiness and they conclude that if the mean received signal strength (RSS) is above -80dBm then the link is almost always good. An exception to this value occurs when people were actively moving between the nodes, in which case there was a grey region of good, intermediate, and poor links slightly below the identified -80dBm threshold.

In [66] the authors performed a set of experiments to get a better understanding of key parameters, namely, the lower link quality threshold level and the hysteresis margin. They conclude that the network perform best when the lower link quality threshold is equal to -90dBm and the hysteresis margin is equal to 5dBm.

In [27] the authors proposed a handoff scheme in which a mobile node constantly monitors the received power from its cluster-head and it triggers a handoff decision when the RSSI drops below a power threshold of -75dBm. Authors justified this value based on previous studies which found that such threshold can guarantee packet reception ratios above 95% ([67], [68]).

In [41], the authors have the mobile node sending periodic probe messages to its current access point and expecting some acknowledgement messages. They measure the RSSI average based of the acknowledgement messages received and if this value
is lower than a predefined threshold the MN initiates the handoff procedure. Using this approach, they managed to reduce unnecessary handoffs.

Based on the aforementioned related work the RSSI threshold value varies from -90dBm to -75dBm depending on the evaluation environment and on the targeted PRR.

It is obvious that the solutions using the RSSI are strongly related to the environment behaviour. Therefore, in case of a highly dynamic environment (like an oil refinery) any RSSI-based mobility solution must consider the signal fluctuations that may affect the correct operation of the handoff procedure. Therefore, more techniques which will select the appropriate triggering and handoff procedures in order to produce a successful necessary handoff, are required.

4.3 Hard Handoff Proposed Mobility Model

As a first step, we implemented the hard handoff where the MN is disconnected first from the current attachment point, it then searches for new possible attachment points, and finally it connects to a new position. As mentioned in the related work section, the RSSI can be used as an indication for the quality of the link and, therefore, in the existence of mobile nodes the RSSI value can be used to trigger the handoff procedure. To perform the handoff, we consider the following triggering options:

1. The MN measures the RSSI value of the link with the parent node. If the RSSI is below a predefined threshold then the MN will de-attach from the tree.
and will set its mode to scan in order to search for a new attachment point. When it finds a new position it will attach to the tree again using topology control signalling.

2. Following a predefined schedule, the MN will set its idle slots to scan mode in order to find a better attachment point. A better attachment point is considered a node with better RSSI value than the existing parent node. If such a node is found, the MN is de-attached from the existing parent and attached to the new parent using again topology control signalling.

![Figure 27: Handoff procedure](image)

The signalling of the proposed solution is presented in Figure 27.

The assumption of the mobility solution as presented in Figure 27 is that the MN is moving in active condition, meaning that data are continuously exchanged between the MN and the neighbouring nodes. However, there is also the possibility
that a MN moves without any communication taking place. Therefore, in such a situation we have to assure that the movement of the MN can be detected. To do so, we use two messages from the DTC module, the Keep_Alive and Node_Alive messages, in order to enable such a scenario. As shown in Figure 28, the Keep_Alive message is periodically (every $x$ interval) sent to the MN by the current parent node. In case the MN does not receive the specific message, it will transmit the Node_Alive message to the current parent node as a trigger to communicate back (using again the Keep_Alive message) to the MN. The interval of the Keep_Alive message is known to the MN since it is a pre-configured value for the whole network. Therefore, if the MN does not receive the Keep_Alive message back, it will set its mode to scan and try to identify a new parent connection.

![Node Detection Diagram](image)

**Figure 28: Node Detection**

In order to obtain the minimum disconnected time during the handoff procedure we must consider the duration of the GinMAC epoch, the available slots (downstream and upstream), and the number of topology related control messages that
must be exchanged in order to reconnect the mobile node. To do so, we assumed
the following parameters as the default values of our case study:

1. Epoch length: 100 slots (10ms each) which equals to 1 second.
2. Slot assignment: 66 upstream, 10 downstream, 22 idle, 2 processing.
3. Control messages: Advertisement, Join, Join acknowledgement.

![Figure 29: Slots Operation](image)

Each node is assigned a specific number of upstream and downstream slots de-
pending on the tree level that it belongs to. In Figure 29 the epoch structure is
depicted as well as the messages and the specific actions of the mobile node dur-
ing the handoff procedure. We will use this Figure 29 to analytically calculate the
handoff delay of the two options, the threshold-based and the RSSI-based. As an
example, we assume that the MN was first connected to the attachment point with
the tree position 2-2-1. As this is a tree-leaf position, the node is assigned two upstream transmitting slots and one downstream receiving slot (Figure 29).

4.3.1 Threshold-based Handoff Decision

In this case, the MN will receive a packet at time $x$ from the parent with RSSI below threshold. At this stage, it will set its slots to scan mode. At time $y$ it will receive an advertisement and if the advertisement is accepted, it will send back a joined message (Join) at time $z$. After that, it will wait to receive the acknowledgement (JoinAck) from the new parent node. The JoinAck is received at time $s$.

To calculate the handoff delay we have to consider the $E$: epoch duration, the $r$: duration of downstream slots, the $d$: the position of previous address in downstream slots and $k$: the position of parent’s new address in downstream slots.

Handoff Delay:

$$3 \times E + k - d$$ (5)

where $d, k \in 0, r$

Therefore, the best case in this solution is $3 \times E - r$ and the worst case is $3 \times E + r$.

4.3.2 RSSI-based Handoff Decision

In this case, the MN will periodically set its idle slots to scan mode in order to search for better attachment points. At time $x$ it will receive an advertisement with better RSSI than that of the parent node and it will send back a Join message at time $z$. After that, it will wait to receive the acknowledgement (JoinAck) from the
new parent node. The JoinAck is received at time $s$. To calculate the handoff delay we have to consider only the epoch duration ($E$) since the $d$ is equal to $k$.

Handoff Delay:

$$2 \times E$$

(6)

Based on the above analysis the minimum disconnection time is equal to two GinMac epochs when we are using the RSSI-based option. Our main target is to ensure that it is possible to control the maximum disconnection time during handoff.

4.3.3 Experimental Evaluation and Performance Analysis

To evaluate the proposed hard-handoff mobility mechanism, a number of tests were conducted in a real testbed. The sensors were configured to send their readings to the sink node every one second, through the constructed tree topology. The tree topology was constructed using the DTC module, as it was described in Section 3.3.1.2. In this set of experiments, we had 9 static nodes and one mobile node operating on a 3-2-1 tree (supports up to 16 nodes). The MN was introduced to the testbed area after the construction of the tree topology and performed random walks in the testbed area. The reason for having fewer nodes than the maximum supported, was due to the fact that we needed to have free positions available for the MN to be attached during the handoff procedure. The tests were mainly performed to evaluate the disconnection time in terms of the time taken to re-attach to the tree. In addition, we monitored the power consumption of the MN.
4.3.3.1 Threshold-based evaluation

We let the fixed nodes to run for a certain time in order to be sure that they are connected properly and our network is operating as expected. After that, we took the sensor node and performed predefined walks inside the testbed. In Figure 30 the sequence number of the packets transmitted/received during the test is depicted. As it can be clearly seen, with one new packet generated per second, the sequence numbers increased monotonically during normal operation. When a handoff occurs, no packets are transmitted, until a new connection is established. This breaks the packet sequence number trend. In this type of experiment, the handoff delay was found to be equal to 2950ms. To calculate this value we monitored the slot numbers where the node was de-attached and re-attached to the tree. Bearing in mind the theoretical analysis of Section 4.3.1, the handoff delay is limited between 2900ms and 3100ms (Equation 15). The testbed evaluation results confirm the mathematical analysis.

![Threshold-based Handoff Procedure](image)

Figure 30: Threshold-based Handoff Disconnection Time
4.3.3.2 RSSI-based evaluation

In the RSSI-based tests we ran a set of experiments by changing the scan interval each time. We used three different intervals (2, 5, 10 seconds) in order to obtain the handoff delay. We used different values of intervals in order to identify the energy overhead of this solution and the number of handoff events that occur in each interval. As before, we let the fixed nodes run for a certain time and then we performed the same walks inside the testbed. Figures 31, 32, 33 show the Packet Sequence number during our walk where in all the cases the handoff delay is equal to 2000ms. The testbed results confirm the mathematical results, as in Equation 6, and also showed that this solution is optimal in comparison with the previous one. In addition, when the interval value is sufficiently large and the RSSI-based equals to 10 seconds, we can observe that there is one handoff event less than in the other intervals.

![RSSI-based interval=2 Handoff Procedure](image)

Figure 31: RSSI-based Handoff Disconnection Time with 2 seconds Interval

In order to understand the energy overhead of our solutions we also measure the power consumption of all the cases. The results are depicted on Figure 79. As
expected, the threshold-based solution presents the lower power consumption. On the other hand, when the scanning option is enabled, in the RSSI-based scenarios, the power consumption is higher. Despite that, when the interval is increased the power consumption tends to be close to that of the threshold-based case. As a conclusion, the decision of what configuration is better, is depends on the scenario requirements and the nodes’ capabilities in terms of energy. The RSSI-based with scanning interval of 10 seconds seems to be a solution that can be used in any case, as it guarantees the minimum handoff delay without introducing a significant energy...
overhead. In addition, in all the scenarios we managed to guarantee that the handoff delay could be controlled.

4.4 No-disruption Handoff Mobility

The first step was to design our mobility solution to support hard-handoff [69] operation. The hard-handoff trigger is initiated based on (i) RSSI threshold and/or (ii) better RSSI value. The specific solution could be suitable for applications with no demanding requirements in terms of packet loss and disconnection time. Based on the evaluation results of the hard-handoff shown in section 4.3 and presented in [69], we managed to guarantee the maximum disconnection time for the mobile node. Table 5 summarises the results that were obtained from hard-handoff solution.

Table 5: Hard-handoff Mobility Disconnection Time

<table>
<thead>
<tr>
<th></th>
<th>Threshold-based</th>
<th>RSSI-based</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoritical Handoff Delay (ms)</td>
<td>Theoritical Handoff Delay (ms)</td>
</tr>
<tr>
<td></td>
<td>2900-3100</td>
<td>2950</td>
</tr>
</tbody>
</table>

Figure 34: Power consumption
In the case of more demanding applications, no disconnection time and packet losses are acceptable, therefore, the hard-handoff solution is not suitable. As a consequence, a no-disruption handoff solution must be implemented. In order to support the attachment of the MN to a new tree position, two additional control messages must be sent. These messages are the Join and the Join_Ack that are sent/received when the MN is still attached to the previous tree position. Therefore, the role of the Dynamic Topology Control (DTC) [57] in no-disruption mobility is to support the re-attachment of the MN to a different tree position as a result of the random walk inside the testbed area. Another critical operation of the mobility algorithm is the triggering of the handoff procedure. Since our main target is to guarantee the performance, the proper module to decide if a MN should handoff or not to a new tree position is the Performance Deduging (Perfd) module. To do so, we set some decision handoff rules in the Perfd module. By initiating the handoff procedure it does not mean that eventually the MN will handoff since there is not any guarantee that the MN will manage to find a better attachment point. Despite that, the fact that there are three free positions for the MN to attach and the fact that the testbed area is not large, increases the probability for the MN to manage to re-attach to a new position.

The no-disruption handoff algorithm is presented in Algorithm 3.
Algorithm 1 No-disruption Mobility Algorithm

if SN then
    Sensor Node: check the children list
    if child_num == 0 then
        No available position(s)
    else
        if child_num != 0 then
            available position(s) advertise
            Adv_Ctrl_Pkt = createAdv(positions(i, . . . , n));
            sendPkt(Adv_Ctrl_Pkt);
        end if
    end if
else
    if join_mm then
        check if the position is still available
        if available then
            accept join, send join_ack and update children list
            JoinAck_Ctrl_Pkt = createJoin(node_id, addr);
            sendPkt(JoinAck_Ctrl_Pkt);
        end if
    else
        do nothing
    end if
end if
else
    if MN then
        Perform Random Walk
        if !attached then
            scan(all_slots);
            receivedPkt(advert);
            Join_Ctrl_Pkt = createJoin(node_id, addr);
            sendPkt(Join_Ctrl_Pkt);
        end if
    else
        if attached then
            set the handoff_trigger
            case 1: Below RSSI threshold
            case 2: Link-Loss Hysteresis threshold
            if handoff_trigger == TRUE then
                scan(idle_slots);
                search for better attachment point based on the RSSI value
                sendPkt(Join_Ctrl_Pkt);
                receivedPkt(join_ack);
                switch to new address
            end if
        end if
    end if
end if
4.5 Handoff Triggering

The first phase of the handoff deals with the initiation/trigerring. A range of metrics could potentially be used in the triggering procedure. In this work, we focus on two easy-to-find local values, namely the RSSI and the Local Link Loss. Using these two metrics, we envisioned several triggering variations like their Simple Moving Average (SMA), Estimated Weighted Moving Average (EWMA) and Burst losses. Figure 35 shows a classification diagram of the triggering solutions.

Figure 35: Single Metric Triggering options

4.5.1 RSSI-based triggering solutions

Regarding the RSSI-based triggering solutions we consider two different options: the threshold-based and the average techniques.

4.5.1.1 RSSI Threshold

In this option, when the RSSI is below a predefined threshold the MN will set its idle slots to scan mode and will start searching for a new point of attachment. The MN will continue to repeat this operation depending on the current RSSI value.
The level of that threshold can be set using the methods found in [10],[70]. This option corresponds to the case 1 of the no-disruption handoff Algorithm 3.

The RSSI Threshold mechanism presented in [70] relies on a single RSSI value to initiate the handoff process, something which leads to unnecessary searches and imposes extra overhead to the system. Based on the related work, we have chosen to extend the RSSI-based triggering method by averaging the received values of the signal. Two approaches that are available in the literature and easily implementable in the resource-constrained sensor nodes are the simple moving average (SMA) and the exponential weighted moving average (EWMA). In the following sections, we are going to examine these solutions and decide if they are applicable for assisting the mobility processes in networks with strict performance needs. An important factor that is also going to be investigated is the ability of the aforementioned averaging solutions to capture the changing and deteriorating link conditions and trigger the handoff on time.

4.5.1.2 RSSI Average Techniques

In order to identify how the use of SMA and EWMA affect the number of triggers, we used an example trace of the RSSI and applied on them the SMA and EWMA formulas.

**Simple Moving Average:** The Simple Moving Average (SMA) is formed by computing the average value of the RSSI over a specific number of periods as shown in Equation 7.
\[ SMA = \frac{RSSI_c + RSSI_{c-1} + \ldots + RSSI_{c-(n-1)}}{n} \]  

(7)

where \( n \) is the size of the moving window and \( c \) is the current value obtained.

Using this equation, it is possible to reduce the unnecessary triggers produced by the fluctuation of the received signal. As we aim to apply this formula for a mobile node, it is important to consider the value of parameter \( n \) since the value of this parameter could affect the on-time handoff.

In addition, Table 6 summarizes the number of triggers for the above cases.

<table>
<thead>
<tr>
<th>Window</th>
<th>Triggers</th>
<th>Scan Epochs</th>
<th>Improvement of triggers and scan epochs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSSI basic</td>
<td>14</td>
<td>499</td>
<td>0/0</td>
</tr>
<tr>
<td>SMA with ( n = 5 )</td>
<td>9</td>
<td>475</td>
<td>35.7/4.8</td>
</tr>
<tr>
<td>SMA with ( n = 10 )</td>
<td>3</td>
<td>469</td>
<td>57.1/6</td>
</tr>
</tbody>
</table>

Based on Table 6, it is obvious that by averaging the RSSI we have less triggers and therefore less energy overhead. In the case of \( n = 10 \) the number of triggers declined from 14 to 3 which means a reduction of 57.1% while in the case of \( n = 5 \) the triggers were reduced by 35.7%. In addition, the number of scan epochs for the two windows of \( n = 10 \) and \( n = 5 \) were reduced by 6% and 4.8% respectively. It is obvious that simple averaging managed to effectively reduce the number of triggers and the power consumption. Despite that, we cannot decide if the simple moving average approach is better than the single value solution, since we first have to identify the effects of averaging the RSSI values on the on-time handoff.

**Exponential Weighted Moving Average:** The Exponential Weighted Moving Average (EWMA) is a type of moving average that is commonly used in network
protocols and favors the established and calculated values over the new measurements. Using EWMA weights we can increase/decrease the importance of the latest RSSI value. Equation 8 shows the way to calculate the EWMA.

\[ EWMA_t = \alpha \times RSSI_{current} + (1 - \alpha) \times EWMA_{t-1} \]  

(8)

where \( t \) is the size of the moving window, \( \alpha \) is the weight given for the last RSSI and \( 1 - \alpha \) is the weight given to the last EWMA value. In addition, \( \alpha \in (0, 1] \) it is calculated based on the following Equation 9:

\[ \alpha = \frac{2}{t + 1} \]  

(9)

Using testbed traces as input in Equation 8, we calculated the number of produced triggers for different values of parameter \( \alpha \) and parameter \( t \). The results are shown in Table 7.

<table>
<thead>
<tr>
<th>Averaging Window</th>
<th>Triggers</th>
<th>Scan Epochs</th>
<th>Improvement of triggers and scan epochs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSSI basic</td>
<td>14</td>
<td>499</td>
<td>0/0</td>
</tr>
<tr>
<td>( t = 3, \alpha = 0.5 )</td>
<td>13</td>
<td>470</td>
<td>7.1/5.8</td>
</tr>
<tr>
<td>( t = 5, \alpha = 0.33 )</td>
<td>11</td>
<td>472</td>
<td>21.4/5.4</td>
</tr>
<tr>
<td>( t = 10, \alpha = 0.185 )</td>
<td>10</td>
<td>469</td>
<td>28.6/6</td>
</tr>
<tr>
<td>( t = 15, \alpha = 0.125 )</td>
<td>10</td>
<td>469</td>
<td>28.6/6</td>
</tr>
</tbody>
</table>

The best results are given when the value of weight \( \alpha \) is less than or equal to 0.185 which means that the window of previous RSSI values is equal to 10. Again, it is important to identify the effects of averaging the RSSI values on the on-time handoff. Figure 36 depicts the comparison between the Single RSSI, SMA RSSI for \( n = 10 \) and EWMA RSSI for \( t = 10 \) for a specific time period.
It is clear that both solutions (SMA and EWMA) managed to reduce the fluctuation phenomena of the Single RSSI solution. Despite that, the EWMA seems to be more prone to fluctuations of the signal compared to the SMA solution. On the other hand, EWMA has the advantage of being quicker to respond to signal trends.

4.5.2 Link Loss-based Triggering Solutions

The main triggering solution related to the Link Loss (LL) is the LL Hysteresis Threshold. In this option, the triggering is initiated if the average percentage of the lost packets between the MN and the parent node communication is above a predefined value $N$. The MN will exit the scanning mode if the link loss value is below the threshold. When the MN handoffs to a new position the average link loss is set to zero. In addition, as in the case of the RSSI, we consider the SMA and the EWMA averaging techniques to be applied to the average Link Loss metric.
The reason of using these techniques is to increase the importance of the latest information since we decrease the data window of the link losses.

4.5.2.1 Burst Loss

The burst loss triggering is initiated when \( n \) continuous packets are lost. Using the same trace as the RSSI-based solutions, we measured the triggers and scan epochs for both solutions. In case of burst loss triggering for \( n > 3 \) the triggers are equal to 10 whereas in case of link loss triggering we have only one trigger for \( N < 25\% \). Regarding the scan epochs the burst loss option produces 10 scan epochs (the same as the burst events) while in the link loss option the MN gets in scan mode for a much larger time period. Figure 37 shows the link and burst losses behavior.

![Figure 37: Burst and Link losses](image-url)
4.6 Handoff Decision

The work presented until now was related to the first phase of a mobility management solution that is the handoff triggering. In this section, we presented the actual handoff decisions. The first decision that was implemented is the commonly used solution that is based on the RSSI hysteresis metric. In addition to the RSSI-based decision, we also introduce the burst probe decision solution.

4.6.1 Hysteresis value

The RSSI-based is the most common handoff decision. As mentioned in the related work section, this decision can be combined with a parameter called hysteresis so that to reduce any effect like the ping-pong phenomenon. Since this is the most commonly used solution, we proceeded with its implementation. In our evaluation tests, we considered the following Algorithm 2 to decide if the handoff will occur or not.

The evaluation of this solution will be mainly used to identify the value of the hysteresis margin that provides the best performance.

4.6.2 Burst Probe using Multiple Attachment Point

In addition to the aforementioned RSSI hysteresis solution, we propose a new handoff decision where the decision to handoff to a new attachment point is based on the comparison of the link loss of the two links, the current and the candidate position. This solution requires the MN to be attached at two points in order to be
Algorithm 2 Hysteresis Margin Handoff Algorithm

if attached then
    set the handoff_trigger
    case 1: RSSI is below threshold
    case 2: LINK LOSS is above threshold
    if handoff_trigger == TRUE then
        set the handoff decision to hysteresis margin
        scan(idle_slots);
        if new position found then
            if new_rssi+hysteresis < current_rssi then
                switch to new address
            else
                disable scan slots
            end if
        end if
    end if
end if

able to test the quality of both links before it decides to handoff. To do so, we send burst probes at the end of each epoch and calculate the acknowledgements. The operation of the burst probe solution is shown below:

4.7 No-disruption Handoff Performance Evaluation using Refinery testbed

In our experiments, the mobile node was introduced into the testbed after the construction of the topology tree (using DTC) and during the tests the mobile user walked randomly for 20 minutes on the refinery testbed area. We assumed a 3-2-1 tree that can support up to 16 nodes. The reason for selecting the 3-2-1 tree is to guarantee that the mobile node has enough available positions (in our case three positions) to be re-attached to the tree. In order to evaluate the handoff triggering mechanisms, we used the COOJA [71] simulator and the radio propagation model
Algorithm 3 Burst Loss Algorithm (BLA) Handoff

```plaintext
if attached then
    set the handoff_trigger
    case 1: RSSI is below threshold
    case 2: LINK LOSS is above threshold
if handoff_trigger == TRUE then
    set the handoff decision to burst probe
    scan(idle_slots);
    if new position found then
        enable burst probing for \( x \) epochs
        compare link loss of the two links using the acks
        if new\_link\_loss + hysteresis\_loss < current\_link\_loss then
            switch to new address
        else
            disable scan slots
        end if
    end if
end if
end if
```

matching that of the refinery testbed (see Section 3.4). The placement of the nodes and the distances between them are the same as in Chapter 3.

4.7.1 Triggering evaluation

In order to evaluate the triggering solutions, we performed 100 runs per parameter combination using 10 different mobility paths. The parameters that were used for our simulations are shown in Table 8.

Table 8: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>2000 seconds</td>
</tr>
<tr>
<td>Testbed Size</td>
<td>35 x 25 meters</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>20 meters</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>100</td>
</tr>
<tr>
<td>Number of fixed/mobile nodes</td>
<td>13/1</td>
</tr>
<tr>
<td>Mobility model/Waypoint paths</td>
<td>Random Waypoint /10</td>
</tr>
<tr>
<td>Packet Rate</td>
<td>1 packet / 3 seconds</td>
</tr>
</tbody>
</table>
4.7.2 RSSI-based Triggering Solutions

In this section, we will use the RSSI with 5db hysteresis handoff decision in order to show the performance evaluation of the three RSSI-based triggering solutions which are the Single-value RSSI threshold, the SMA threshold and the EWMA threshold.

4.7.2.1 Single-value RSSI Threshold Evaluation

In order to evaluate the Single-value RSSI threshold, we ran the experiments using an RSSI triggering threshold of -78dB and a hysteresis margin of 5dB to initiate the trigger and to perform the handoff respectively. Table 9 shows the overall results of the experiments. We observed that, the End-to-End packet loss is equal to 4.2% while on average we have 5.28 triggers and 0.14 handoffs. The percentage of triggers which have led to handoff is 2.8%, which is low. In addition, the total power consumption is equal to 0.41mW.

<table>
<thead>
<tr>
<th>Average End-to-End Packet Loss [%]</th>
<th>Average Number of Triggers</th>
<th>Average Number of Handoffs</th>
<th>Trigger Success Ratio [%]</th>
<th>Power Consumption [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>5.28</td>
<td>0.14</td>
<td>2.8</td>
<td>0.41</td>
</tr>
</tbody>
</table>

4.7.2.2 RSSI SMA and EWMA Evaluation

One important parameter of the SMA solution is the size $n$ of the moving window, which indicates the number of previous packets that are considered. In this section, we have used two different values for $n$. We selected the window to be equal to 5
and 10. Figure 38 shows the results. We can observe that, for $n = 5$ we measured slightly less End-to-End packet loss compared to $n = 10$. On the other hand, the window size of 10 produced less triggers and more handoffs and as a consequence higher trigger success ratio.

![SMA Evaluation.png](attachment:SMA_Evaluation.png)

Figure 38: SMA Triggering Evaluation

In addition to the above metrics, Figure 39 shows the total power consumption of both window sizes. We observe that, for $n = 10$ the total power consumption is less compared to $n = 5$. This is due to the fewer number of triggers and therefore to less scanning epochs.
Due to the fact that we have mobility and, therefore, a dynamically changing environment, the window size cannot be set to high values because it will totally smooth the RSSI and therefore it will ignore significant events. On the other hand, a low window size will not reduce the signal fluctuations effects. Based on the evaluation, we can conclude that the benefits of using \( n = 10 \) are more compared to \( n = 5 \).

On the other hand, the \( t \) value in EWMA corresponds to the weight which is assigned to the current and previous RSSI values based on the equation 9. Figure 40 depicts the overall performance evaluation of the EWMA solution. As we observe, for \( t = 5 \) we achieved the minimum packet loss and the highest success ratio.

In addition, Figure 41 presents the power consumption of three \( t \) values where we conclude that they show similar behaviour.

Figure 39: RSSI SMA Triggering Power Consumption Evaluation
Based on the evaluation, we conclude that the benefits of using $t = 5$ are more compared to the other two options.

### 4.7.3 Link-Loss Triggering Evaluation

In addition to the RSSI-based solutions, we evaluated the Link-Loss based solution using different threshold losses. We select the thresholds to be equal to 1%, 5%, 10% and 15%. Figure 42 shows the results of our experiments.

It is clear that, for the specific metrics, we achieved the best performance in terms of End-to-End packet losses when the Link-Loss threshold was set to 1% with the threshold value of 5% to follow in performance. Furthermore, lower thresholds provide higher success ratio since the MN operates more in scanning mode, therefore it could easier find a better attachment point.

Additionally, Figure 43 shows the total power consumption of all the link loss threshold options.
As it can be seen, the power consumption is linearly increased as the threshold value is decreased. This is due to the more scanning epochs and therefore to more reception slots.

4.7.3.1 Link Loss SMA and EWMA Evaluation

In addition to the Link-Loss based solution using different threshold losses, we used the SMA and the EWMA averaging methods in order to increase the weight of the latest link losses. Figures 44 and 45 show the behaviour of the system when we use the SMA option for $n = 10$ and $n = 20$. It was observed that, considering the End-to-End packet losses, the differences are negligible. On the other hand, we observe that, as the thresholds and the window size are increased, the success ratio is increased and the power consumption is decreased.

In addition to the SMA option, we repeated the experiments using the EWMA option. Based on the results shown in Figures 46 and 47 the End-to-End packet loss
is decreased as the threshold value is decreased but low threshold selection affects negatively the power consumption.

4.7.3.2 Burst Loss Triggering Evaluation

The final triggering solution is based on the burst losses monitoring. So, if we identify that we have more than \( n \) consecutive losses, where \( n \) is set to 3 packets, we initiate the triggering procedure. We measured the End-to-End packet loss being equal to 4.3\%, the average triggers equal to 1.7 and the average handoffs equal to 0.02. Finally, the total power consumption was equal to 0.4 mW. Based on the results, we can observe that in the Burst triggering solution the number of triggers and handoffs are reduced to the minimum values compared to any other solution; although the End-to-End packet loss remains high. This behaviour is due to the fact that the burst losses occur instantaneously with small duration, therefore, the MN
will immediately stop searching for new attachment point, something which reduces the possibility to handoff.

### 4.7.4 Comparison of Triggering Solutions

Based on the aforementioned evaluation results, we compare the four triggering solutions using their best combination. Figure 48 depicts the comparison of the average End-to-End packet loss. We can observe that the lowest packet loss is shown in the case where we use the Link Loss triggering options. This is due to the fact that in our setting the losses occurred in bursts, therefore since Link Loss is based on the average link loss it can easier respond to link quality degradation. Furthermore, the RSSI averaging solutions (SMA, EWMA) minimized the packet loss compared to the RSSI simple-value threshold.

In addition to the above, we proceeded with the comparison of all the solutions based on their effectiveness to initiate a trigger when an End-to-End packet loss
event occurs. We considered that such an event exists if we have two consecutive packets lost. We call this effectiveness, as *on-time* triggering. We need to mention that the on-time triggering is the only metric which is not related to the system limitations, like the available free positions. As such, it will give a better indication of the best triggering solution. Figure 49 shows the result of the comparison.
Figure 45: Link Loss SMA Triggering Power Consumption Evaluation

We can conclude that the Link loss options, in general, present higher on-time success than the other solutions. More specifically, the LL=1% threshold is the option with the highest on-time success which reached a value of up to 55.3%. On the other hand, the RSSI threshold also presents high on-time success with a value of 42.4%. We also observe that when using averaging methods, the on-time success is decreased.

Table 10 depicts the comparison of the best option of each proposed solution. We observe that the Link Loss triggering option with 1% threshold presents less End-to-End packet losses. This is due to the fact that, with this option, the MN operates in scanning mode for longer period of time therefore it will manage to find a better attachment point, if any, to handoff. Despite that, we can observe that even though the Link-Loss based solution has the highest success ratio, it increases the power consumption. This is also due to the fact that the Link Loss threshold value of 1% is too low, so the MN will be in scan mode for longer period than the other
solutions. The same is true when using averaging methods for the Link Loss metric. Considering all the evaluation metrics, we can not easily select the best option since there is a trade-off between End-to-End packet loss, power consumption and on-time triggering. If, for example, the power consumption is not of high importance and the target is to reduce the End-to-End losses, then the average Link-loss metric with the 1% threshold is the best solution. If energy is the most important metric, and End-to-End loss, as on-time triggering is of low importance, then we need to select an averaging solution minimizing the power consumption which could be the EWMA of Link Loss. Based on the overall evaluation, we can conclude that if the power consumption is not important (e.g. scenarios where energy harvesting is possible), we can use the Link-Loss based solution, otherwise we can use the RSSI SMA solution.
Figure 47: Link Loss EWMA Triggering Power Consumption Evaluation

Figure 48: Overall Packet Loss Comparison

4.8 Handoff Decision evaluation

In order to evaluate the triggering and handoff decision, we used the COOJA [71] simulator and the refinery radio propagation model (see Section 3.4). The parameters we used for our simulations are shown in Table 8. The first evaluation sub-section deals with the hysteresis margin evaluation, whereas the second deals with the evaluation of all possible triggering and handoff combinations. To do so, we
Table 10: Experimental Results

<table>
<thead>
<tr>
<th>Solution</th>
<th>Packet Loss[%]</th>
<th>Total Power Consumption [mW]</th>
<th>Success Ratio</th>
<th>Average Triggers</th>
<th>Average Handoffs [%)</th>
<th>On-time</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSSI Threshold, -78dBm</td>
<td>4.1</td>
<td>0.39</td>
<td>2.8</td>
<td>5.28</td>
<td>0.14</td>
<td>32.4</td>
</tr>
<tr>
<td>EWMA RSSI, $t = 5, a = 0.33$</td>
<td>3.47</td>
<td>0.368</td>
<td>23</td>
<td>0.77</td>
<td>0.17</td>
<td>17.92</td>
</tr>
<tr>
<td>SMA RSSI, $n = 10$</td>
<td>3.45</td>
<td>0.37</td>
<td>33.3</td>
<td>0.42</td>
<td>0.14</td>
<td>22.2</td>
</tr>
<tr>
<td>Link Loss, Threshold 1%</td>
<td>2.42</td>
<td>3.11</td>
<td>16.05</td>
<td>2.25</td>
<td>0.36</td>
<td>45.3</td>
</tr>
<tr>
<td>EWMA Link Loss 10%, $t = 5, a = 0.33$</td>
<td>2.41</td>
<td>0.79</td>
<td>12.85</td>
<td>2.88</td>
<td>0.37</td>
<td>21.6</td>
</tr>
<tr>
<td>SMA Link Loss 10%, $n = 10$</td>
<td>2.43</td>
<td>0.85</td>
<td>1.85</td>
<td>22.12</td>
<td>0.41</td>
<td>38.9</td>
</tr>
<tr>
<td>Burst, $n = 3$</td>
<td>4.3</td>
<td>0.39</td>
<td>1.2</td>
<td>1.7</td>
<td>0.02</td>
<td>47.4</td>
</tr>
</tbody>
</table>

run 100 different simulations for each combination using 5 different mobility paths based on the Random Waypoint model.

4.8.1 Hysteresis Margin Evaluation

In order to evaluate the hysteresis margin, we considered both triggering options: the Link Loss and the RSSI Threshold-based. In the RSSI Threshold triggering solution, we set the threshold value to -78dBm, a value extracted from long-term runs inside the refinery environment ([10],[70]). In addition, we selected the average Link Loss (LL) threshold triggering values to be equal to 1%, 5%, 10% and 15%.

Figure 50 shows the overall evaluation in terms of average End-to-End packet loss, average number of triggers, average number of handoffs, and the percentage of triggers that led to handoff (triggers success ratio) for different hysteresis values using the Link Loss triggering option.

Based on the results, the lower packet loss is observed when the hysteresis value is equal to 5dBm using Link Loss=1%. We can further observe that as the Link Loss threshold value is increased, the packet loss is also increased in all the hysteresis
Figure 50: Hysteresis Margin - Link Loss Triggering

margins. This is due to the fact that the increase of the Link Loss threshold value leads to fewer scanning periods, and as a consequence to a lower probability to find a new attachment point that meets the handoff requirements. The best scenario (5dBm with LL=1%) presents 4.2% fewer losses compared to the 3dBm hysterisis, 0.57% fewer losses compared to the 3dBm hysterisis, 1.67% compared to 2dBm, and 12.2% compared to 1dBm. With regards to the total packet loss (using all the Link Loss triggering solutions) the different hysteresis margins present the same behaviour. Regarding the number of triggers, number of handoffs, and the triggers success ratio the different hysteresis margins present similar behavior.

We repeated the simulations using the RSSI Threshold triggering and the results are shown in Figure 51.

We observed that the lower packet loss is shown when the hysteresis is equal to 5dBm. However, the 5dBm hysteresis margin presents the higher number of triggers
and low trigger success ratio. This is due to the fact that the RSSI Threshold triggering is event based due to the fluctuations and the dynamic nature of the physical environment. As such, the duration of the scanning period is small and therefore the probability to find new attachment point is decreasing as the hysteresis margin is increasing. This is more clear when using hysteresis equal to 10dBM.

In addition, Figure 52 depicts the power consumption of the solutions. It is obvious that the power consumption depends mostly on the triggering decision and not on the hysteresis margin.
Based on the results shown in Figure 50 and Figure 51, it is difficult to extract safe conclusions regarding the importance of the hysteresis margin value. This is mainly due to the fact that the results above involve all the scenarios including those where no trigger/handoff occurred. In addition, there is no guarantee that the MN will manage to find a new attachment point with better signal quality. Therefore, we only used the simulations where a handoff event occurred and we used a set of metrics (packet loss, ping pong, and number of triggers) in order to evaluate the behaviour of the system for a short period $T$ after the handoff. These metrics will help us to indicate the effectiveness and the correctness of the handoff events.

Figure 53 depicts the End-to-End packet loss after the handoff for $T = 15$ seconds. Based on this figure the lower packet loss occurs when the hysteresis margin is equal to 5dBm. More specifically, the 5dBm margin produced 7.1% fewer losses
compared to 10dBm, 6.4% fewer losses compared to 3dBm, 1.2% fewer losses compared to 2dBm and 0.8% fewer losses compared to 1dBm.

Figure 53: Handoff Effectiveness - Packet Loss after Handoff

Figure 54 depicts the number of ping-pong events for $T = 15$ seconds after a handoff event occurred. We observe that hysteresis margin of 5dBm produced the least ping pong events than any other margin value. Particularly, compared to 10dBm, it produced 12.5% less ping pong events, 61% less ping pong events compared to 3dBm, 59% less ping pong events compared to 2dBm, and 77% less ping pong events compared to 1dBm.

Finally, Figure 55 shows the number of triggers which have occurred after a handoff event. Again the hysteresis margin of 5dBm presents the lowest number of triggers.
It is obvious that the 5dBm hysteresis presents the best performance, since the packet loss after the handoff event is lower than the other margins, it produced fewer triggers and it managed to keep the ping-pong events to low values.
4.8.2 Evaluation of handoff combinations

In total, we have four combinations arising from the two triggering (RSSI Threshold and Link Loss) and the two handoff decision (RSSI Hysteresis and BLA) options. We set the RSSI Threshold and the Link Loss to the values used in the hysteresis margin evaluation. In addition, based on the RSSI hysteresis evaluation we set the hysteresis to 5dBm. In order to evaluate the BLA handoff solution, we set the BLA hysteresis loss value to 0%, 5%, 10% and 15%.

Figure 56 shows the End-to-End packet losses for all the possible combinations of the aforementioned triggering and handoff decision options. We can observe that the lowest packet loss is achieved with Link Loss triggering (LL=1%) and hysteresis 5dB decision.

Another observation, using the Link Loss triggering and the 5dBm decision, is that as the hysteresis threshold increases the End-to-End packet loss increases as well. On the other hand, in the scenarios where the handoff decision was set to BLA,
we observe that the End-to-End packet loss decreases as the link loss hysteresis is increases. In addition, the lowest packet loss using the BLA option is observed when Burst=5%.

Figure 57 shows the average number of triggers for all the combinations. It is obvious that the Link-Loss triggering option produces a lot more triggers than the RSSI threshold triggering. This is due to the selection of value of the Link Loss hysteresis threshold, since a low hysteresis value will initiate a trigger when only a few packets are lost. In addition, we can observe that as the link loss hysteresis threshold increases the number of triggers decreases. Therefore, we can conclude that the overhead added to the system is higher when the link loss hysteresis threshold is set to low values.

Figure 57: Average Number of Triggers

Figure 58 depicts the number of handoffs per combination. As it was expected, the number of handoffs relates to the number of triggers. However, it does not mean
that a handoff could lead to a better performance since the new position may have a worse performance than the existing one.

![Number of Handoffs](image)

Figure 58: Average Number of Handoffs

Furthermore, Figure 59 shows the triggering success ratio.

![Success Ratio](image)

Figure 59: Success Ratio
The higher the success ratio the lower the overhead, since high success ratio indicates more triggers which led to handoff. Based on Figure 59 the highest success ratio occurs when the Burst is equal to 5%.

Figure 60 shows the total power consumption. As it can be seen, the Link Loss-based solution with low link loss hysteresis shows increased power consumption. As the hysteresis loss threshold increases, we observe that the power consumption is reduced. This is due to the fact that a low link loss hysteresis will force the MN to be at a scanning mode for a longer period of time, thus the reception power consumption is increased. In addition, we see that Burst=5% is the solution with the lowest energy overhead mostly due to the fact that it provides the highest triggering success ratio.

![Figure 60: Total Power Consumption](image)

From the results of the simulations presented above, we can conclude that a value of 5% as the hysteresis loss in the BLA algorithm seems to be the best, since it operates with the lowest number of triggers, the highest number of handoffs, the
highest success ratio, the lowest energy overhead, and the lowest packet loss from all other combinations. However, it demonstrates a higher End-to-End packet loss than the RSSI hysteresis margin (Hyst=5dBm). This observation indicates that we must further investigate the behaviour of the solutions. For this reason, we used the handoff effectiveness analysis, which is based on three metrics, the average packet loss after the handoff event, the number of ping-pong events and the average triggers after handoff. Using this set of metrics, we can conclude the correctness or not of the handoff event.

Figure 61 shows the packet loss for a short period (\( T = 15 \) seconds) after the handoff event. It is obvious that the lowest packet loss is experienced in the Burst=5% option.

![Figure 61: Packet Loss after Handoff](image)

Figure 62 depicts the average number of triggers after a handoff event. Again, we can see that Burst=5% has the best performance compared to the other BLA
options. On the other hand, we observe that it performs almost the same as the Hyst=5dBm option.

Finally, Figure 63 shows the number of ping pong events after the handoff.

We observe that RSSI hysteresis of 5dBm produces fewer ping pong events compared to any other solution, regardless of the triggering option. The reason for this is the high hysteresis margin that was set (5dBm). The only option where BLA and
RSSI hysteresis options show the same performance is when the trigger occurs using the Link Loss hysteresis threshold of 15% and BLA equal to 5%.

In general, the results show that there is not any global way to select the pair of triggering and handoff decision. The RSSI-based hysteresis margin of 5dBm seems to perform better than the BLA in terms of the overall End-to-End packet loss where the BLA with hysteresis loss equal to 5% performs better in all other metrics than any other solution. The reason for this behaviour is the increased ping-pong events that occurred in the case of the BLA option evaluation. Based on that, we proceeded with a new set of simulations in order to identify how the performance changes in the presence of both handoff decision rules. Based on the results shown above, we selected the RSSI hysteresis value equal to 5dBm and the BLA value equal to 5%. In addition, we selected the LL=15% and RSSI Threshold=-78dBm to be the triggering options. We repeated the simulations and the results which are shown in Table 11.

Table 11: Experimental results

<table>
<thead>
<tr>
<th>Solution</th>
<th>Packet Loss [%]</th>
<th>Number of triggers</th>
<th>Number of handoffs</th>
<th>Triggers after handoff</th>
<th>Ping Pong</th>
<th>Losses after Handoff</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL, T=5%</td>
<td>3.1</td>
<td>12.41</td>
<td>0.8</td>
<td>0.3</td>
<td>15</td>
<td>3.1</td>
<td>0.5</td>
</tr>
<tr>
<td>LL, T=5%,5dBm</td>
<td>2.46</td>
<td>4.54</td>
<td>0.45</td>
<td>0.33</td>
<td>2</td>
<td>3.3</td>
<td>0.52</td>
</tr>
<tr>
<td>RSSI, 5dB</td>
<td>4</td>
<td>9.85</td>
<td>0.16</td>
<td>0</td>
<td>0</td>
<td>15.1</td>
<td>0.41</td>
</tr>
<tr>
<td>RSSI, T=5%,5dBm</td>
<td>3.7</td>
<td>6.7</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The results show that the combination of handoff criteria indeed improve both the overall and the after-handoff performance, especially when using the RSSI thresholding with hysteresis margin option. In the case of RSSI thresholding with
both handoff decisions, we observe that the End-to-End packet loss is reduced by 7.5% compared to hysteresis margin single decision, while the packet loss, just after the handoff, is reduced by 67%. In addition, the triggering success ratio is increased from 1.6% to 2.3% and the power consumption is decreased by 2.5%. There is no change to the ping-pong events and triggers after handoff. On the other hand, concerning the combination of Link Loss triggering with BLA handoff decision, we observe that the End-to-End packet loss is reduced by 20.6% compared to single BLA handoff. In addition, the triggering success ratio is increased from 6.4% to 9.9%. Furthermore, the ping-pong events are reduced by 87%, whereas the triggers and losses after handoff do not show a remarkable difference.

Based on the performed evaluation, it is clear that in the case of the Link Loss triggering with BLA (Burst=5%) handoff the problem was the increased number of the ping-pong events. Thus, when we added the hysteresis margin of 5dBm in the handoff decision, we observed that the packet losses after the handoff did not change, but the End-to-End losses were reduced by 20.6%. On the other hand, in the case of RSSI triggering with hysteresis margin of 5dBm, we observed that the addition of BLA handoff improved the performance mostly during the handoff decision since it reduced the packet losses after the handoff by 67%.

Based on that, we can conclude that the single BLA handoff performs better than the hysteresis margin handoff but suffers from ping-pong events. On the other hand, the hysteresis margin managed to reduce the ping-pong events. Thus, the
combination of both handoff decisions outperforms any single-based handoff decision.

4.9 Single Metric-based Handoff Summary

In this chapter, we have investigated the applicability of single metric-based solutions to support the triggering and the decision phases of the handoff procedure. We have selected two easy to find metrics, namely RSSI and Link Loss, and several ways of measuring them like averaging techniques (SMA, EWMA) and burst approach.

We performed an extensive evaluation of the several solutions in order to discover the proper value of several parameters like the hysteresis margin and the triggering thresholds. We proceeded with the combination of different triggering and decision options in order to identify the best combination. In addition, two evaluation metrics were used so that to help with the evaluation and comparison of the different solution options. These metrics are the on-time triggering and the handoff effectiveness.

Despite the fact that the several single-based approaches managed to reduce the End-to-End packet loss, there are some drawbacks that someone could use to argue that a better solution is needed. Based on our evaluation regarding the proper triggering and handoff decision, we concluded that as far as the triggering options are concerned, there is a trade-off between the different metrics and the selection of the best option depends on the application requirements. It was clear, that when using the link loss approaches the packet loss was decreased but this was due to the
fact that the MN was continuously scanning for new attachment points, therefore if any better attachment point was available for the MN it was used to handoff. But this approach has one major drawback: the increased scanning periods and therefore the increased power consumption. In case of RSSI-based solutions, the power consumption is not a major issue. The RSSI-based solutions suffer from the wrong triggering and low on-time triggers due to the unpredictable radio conditions in the refinery area. On the other hand, the handoff decision evaluation shows that a combination of both options (BLA and RSSI hysteresis margin) is the best solution.

4.10 Single Metric-based Handoff Discussion

The main drawback of the triggering solutions, is the fact that the decision is depended on a single matric value (RSSI or Link Loss). Based on our evaluation results, we have seen that there is not any single-based solution that could be used to achieve the targeted performance requirements.

The second drawback is the fact that the solutions that have reduced the End-to-End packet loss, have at the same time, shown increased power consumption or shown low on-time triggering. Therefore, we conclude that we need an improved solution that will use the full system capabilities and which will manage to fulfil all the targeted performance requirements. Consequently, we decided to consider both, the average link loss metric along with RSSI, in order to support the handoff procedure. In other words, to combine the two single metrics. The reason behind the selection of the link loss metric and the RSSI was the fact that both metrics
are available at each MN. The distributed nature of a distributed approach allows
the system to adapt quickly to disturbances or changes within the network in real-
time. As a first step, we run some experiments at the SINES testbed area to
extract information regarding the relationship of the End-to-End losses, RSSI and
Link losses. The reason for not directly using End-to-End packet loss is that this
information is not available at each node but only in the end system (sink node).
Therefore, we need to somehow “predict” the value of the End-to-End loss using
other metrics that are available to each node. The results of those experiments are
shown in Figure 64. Based on Figure 64, we can conclude that indeed we can use
a combination of RSSI and link loss metrics in order to “predict” the End-to-End
losses and support the handoff triggering procedure.

![Figure 64: End-to-End loss, Link Loss and RSSI relation](image)
Figure 64 shows that when the link loss is above 15% and the RSSI is less than -78dB, the End-to-End packet loss is increased. Another conclusion is that when the RSSI is good enough (greater than -60dB) and the link loss is up to 40%, the End-to-End packet loss is acceptable. This behaviour is due to the ability of the mobile node to retransmit the packets in case the communication link between MN and parent node is good. Therefore, low End-to-End packet loss can be achieved by minimizing the link loss and maximizing the RSSI. In order to exploit the above conclusions, we decided to investigate the use of Fuzzy Logic techniques. The fact that Fuzzy Logic can handle multiple inputs effectively with low overhead is an extra positive of selective it to support our mobility solution. As Fuzzy Logic can combine RSSI and Link loss metric information, we expect that Fuzzy logic will allow us to minimize the End-to-End packet loss, to minimize the total number of triggers, and the success ratio of triggers, handoffs and also the on-time triggering.

We expect that Fuzzy logic will allow us to minimize the End-to-End packet loss, as it will combine RSSI and Link loss metric information, to minimize the total number of triggers, maximize the success ratio of triggers, handoffs and on-time triggering.
Chapter 5

Fuzzy Logic-based Mobility solution

5.1 Introduction

In this chapter, a Fuzzy Logic-based solution is proposed that does not change the existing conventional algorithms but instead uses their functions in order to provide a system that will manage to control the handoff procedure and provide improved performance. However, the motivation of the work in this chapter is the fact that there is no protocol designed and evaluated to support the mobility process in critical environments; thus, this work provides an effective solution to this missing piece. This issue is considered of the utmost importance for today’s real-world industrial applications. The reason for selecting Fuzzy logic for our mobility scenario is threefold:

1. It can control nonlinear systems (such is our system) that would be difficult or impossible to model mathematically.
2. Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter the system performance.

3. It can handle multiple inputs, something that based on the conclusions of Chapter 4 is of high importance.

5.2 Related Work

The main issue of using RSSI metric individually is the unpredictable behaviour it may display in a harsh radio environment. Recently, some work has come to light proposing the use of heuristic models, like fuzzy logic, to support the hand-off triggering decision. In [41] authors provide a fuzzy logic system to support the mobility procedure based on RSSI level, velocity of mobile node, number of hops to sink node, and some other metrics such as traffic load, energy level, and link quality value. Although they discussed in detail their solution they did not provide any implementation or evaluation of it. Therefore, the applicability of their solution and possible overheads are undetermined. In addition, the high number of metrics that they aim to use will lead to an increased fuzzy logic complexity since a big number of rules must be enabled at any time. Due to the limited capabilities of the sensor nodes, a fuzzy logic based system must be as simple as possible. In [40], a handoff decision for heterogeneous networks is identified as a fuzzy multiple attribute decision-making problem, and fuzzy logic is applied to deal with the imprecise information.
In order to support the complex situations of mobility management such as the triggering procedures, mobility management solutions can use tools from the family of Computational Intelligence (CI). In [72], CI is defined as *the computational models and tools of intelligence capable of inputting raw numerical sensory data directly, processing them by exploiting the representational parallelism and pipelining the problem, generating reliable and timely responses and withstanding high fault tolerance.* Several examples of application of such CI tools were presented in the literature but whose prime focus is not WSNs. Recently, researchers started thinking of ways to use CI tools in order to solve WSN issues such as design and deployment, localization, security, routing, data aggregation and QoS management. Examples of such work are presented in [73], [74] and [75]. An overview of the CI techniques in WSNs are presented in [5], where authors findings have been summarized in Figure 65.

![Figure 65: WSN challenges and CI paradigms](image)

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**Figure 65: WSN challenges and CI paradigms [5]**
It was obvious to us that several parameters can affect the triggering and the handoff procedures especially when the targeted environment is an industrial field. Therefore, techniques that will distinguish triggering and handoff procedures and also combine available information in order to produce a successful necessary handoff are required.

5.3 Handoff Control in Industrial WSNs

This section presents the drawbacks of the RSSI Threshold-based solution in industrial environment and outlines the design requirements for schemes involving fuzzy-based logic.

5.3.1 RSSI Threshold-based Handoff Decision

Prior work presented in Chapter 4 has used RSSI threshold as a handoff control method in critical application scenarios, including industrial cases. Based on the referenced works, the handoff decision rule used was: *If the RSSI of the communication link between the MN and the current parent is below a predefined threshold $H$ then the MN will trigger a handoff.* This option was named RSSI Threshold handoff.

The rule outlined above was evaluated in a set of experiments using the oil refinery testbed at our disposal. The testbed network architecture comprised of three kinds of nodes: one sink node, twelve static nodes, and one mobile node organized in the same type of topology considered in the above referenced works. The mobile node was introduced into the testbed after the construction of the topology tree.
and during the experiments the mobile user walked randomly for 20 minutes in the refinery testbed area. An example of the behaviour of the RSSI parameter during a random walk in the refinery environment is shown in Figure 66.

![RSSI behaviour in Refinery environment](image)

**Figure 66: RSSI Behavior in the Refinery Testbed.**

Table 12 summarizes the average results obtained through this experimentation. It is obvious that the conditions inside the refinery testbed area are highly unpredictable. Furthermore, it is observed that the measured average packet loss is equal to 8.11%, while the ratio of the successful triggers is only 4.15%.

<table>
<thead>
<tr>
<th>Packet Loss (%)</th>
<th>Total RX Energy (J)</th>
<th>RX Energy (J)</th>
<th>TX Energy (J)</th>
<th>Triggers No.</th>
<th>Handoffs No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.11</td>
<td>0.57</td>
<td>0.51</td>
<td>0.057</td>
<td>108.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Table 12: RSSI-Threshold Results**

The main drawback of the RSSI threshold solution is that it has an End-to-End packet loss rate which is very high by any standard. According to [76] and [77] acceptable values for End-to-End packet loss are between 1% and 3%.
5.4 Proposed Intelligent Fuzzy Logic-based Mobility Controller

The Fuzzy Logic-based Mobility Controller (FLMC) is designed to enable any wireless sensor MN to decide intelligently whether the handoff procedure has to be triggered. The approach taken has greater applicability to any WSN industrial environment or testbed setting with mobility requirements, since it is designed based on network state parameters that are available to all wireless sensor MNs. The selection of fuzzy logic control is based on its simplicity and the fact that since it processes experts-defined rules governing the target control system, it can be easily modified to improve system performance.

A simple fuzzy inference engine (FIE) is designed to operate locally at each sensor MN, and control the handoff decision procedure, using linguistic rules that describe the behaviour of the environment in differing widely operating conditions. The FIE implements a nonlinear decision point (to trigger the decision whether a sensor mobile node has to handoff to a new position or not), and uses feedback from both the instantaneous value of the signal strength indication (RSSI) and the Link Loss rate, both sampled periodically. By having a nonlinear control law, based on fuzzy logic, the aim is to effectively deal with the high variability and dynamics appearing in the network, and thus exhibit fast system response and robust behavior in spite of varying network conditions. Thus, a nonlinear control law is more efficient to cope with these uncertainties and dynamics, in contrast with a linear control method.

There is no accepted systematic procedure to design a fuzzy controller [4]. The most commonly used approach is to define membership functions of the inputs and
output based on a qualitative understanding of the system, together with a rule data
base, and to test the controller by trial-and-error until satisfactory performance is
achieved. More sophisticated techniques abound, however, we opt for this simple
approach which also yields a simple implementation, and as we show later is effective.
We rely on the use of heuristic expertise and study of the plant dynamics about
how to best configure the control law. The main focus is on the achievement of the
mobility requirements indicated in Table 2 — Section 3.3.3, whilst keeping the design
of the controller as simple and generic as possible. Thus, concerning the limitations
that arise from sensor networks, this method seems to be a suitable approach for our
system. Note that as the fuzzy controller is nonlinear, it is very difficult to examine
analytically the influence of certain parameters. Usually, extensive simulation and
experimentation are used to investigate its behaviour. However, a system’s stability
technique is followed (more later, — Section 5.6) that verifies that the states of the
system remain within specific bounds.

Our aim is to ensure that the controller will have the proper information available
to be able to make good decisions, and will have proper control inputs to be able
to steer the controlled system in the directions needed, so that it achieves a high-
performance operation, as pointed out above. Some of the design choices are briefly
described below.
5.4.1 Selection of Input-Output and Scaling

Since multiple inputs can usually capture the dynamic state of the controlled system more accurately, and also can offer better ability to linguistically describe the system dynamics [4], we utilize a two-input, single-output (simplest of the Multiple Input Single Output (MISO) model) fuzzy controller on each sensor MN in WSNs. There is a need to choose the right inputs and output with generic normalized universe of discourse (more later), applicable in any setting. We select the RSSI and the Link Loss, two distributed locally available metrics, in order to ”predict” the End-to-End losses and support the handoff triggering procedure. The influence of these two metrics on attempting to predict the End-to-End loss was shown and discussed in – Section 4.10 (also, see Figure 64). Further, the output of the controller is selected as a nonlinear decision point that is given as input of the controlled system in order to decide whether to trigger a handoff procedure. After all the inputs and the output are defined for the proposed FLMC controller, we specify the fuzzy control system shown in Figure 67, where all quantities are considered at the discrete instant kT:

1. T is the sampling period. The sampling period is equal to the time bound Ts.

2. RSSI(kT) is the signal strength indication, taken every sampling period.

3. LL(kT) is the link loss rate measured at each sampling period.

4. Pd(kT) is the calculated decision point that triggers the handoff procedure.

5. \( SG_{i1,2}(kT) \) are the input scaling gains.
6. $P_{\text{Threshold}}$ is a predefined threshold that indicates if the specific $Pd(kT)$ will trigger the handoff.

In fuzzy control theory, the range of values of inputs or outputs for a given controller is usually called the “universe of discourse”. Often, for greater flexibility in fuzzy controller implementation, the universe of discourse for each process input is “normalized” by means of constant scaling factors [4]. For the fuzzy controller design developed here, the input scaling gains, $SG_{i_1,2}(kT)$, are inherently chosen so that the range of values $SG_{i_1}(kT)\text{RSSI}(kT)$ and $SG_{i_2}(kT)\text{LL}(kT)$ lie in the real interval $[0, 1]$ (see Eq. (10),(11)).

\begin{equation}
SG_{i_1}(kT) = \frac{1 - \frac{\text{RSSI}_{\text{min}}}{\text{RSSI}(kT)}}{\text{RSSI}_{\text{max}} - \text{RSSI}_{\text{min}}} \tag{10}
\end{equation}

\begin{equation}
SG_{i_2}(kT) = \frac{1}{100} \tag{11}
\end{equation}

where $\text{RSSI}_{\text{min}}$ and $\text{RSSI}_{\text{max}}$ were obtained during the experiments conducted in the setup phase of the oil refinery testbed.
5.4.2 Selection of Rule Base, Linguistic Variables and Values

The multi-input FIE uses linguistic rules to calculate dynamically the decision point. These linguistic rules form the control knowledge — rule base of the controller and describe how to best control the system, under differing operating conditions. Hence, linguistic expressions are needed for the inputs and the output, and the characteristics of the inputs and the output. “Linguistic variables” (that is, symbolic descriptions of what are in general time-varying quantities) are used to describe fuzzy system inputs and output. The linguistic variables take on “linguistic values” that change dynamically over time and are used to describe specific characteristics of the variables; such values are generally descriptive terms such as “low”, “medium” and “high”.

The linguistic variables and values provide us a language to express our ideas about the control decision-making process in the context of the framework established by our choice of FLMC controller inputs and output. In order to determine the linguistic values of the input and output variables, we need to define partitions over the input and output space that will adequately represent the linguistic variables. Since the inputs of the FLMC controller deal with the RSSI and Link-Loss evolution, which is dynamic and time-varying in nature, we need to have as “many” operating regions — state partitions as possible, in order to capture as much detail of the dynamics and the nonlinearities of the system plant. However, we also need to keep the controller as simple as possible by not increasing the number of linguistic values — state partitions beyond a number, which does not offer significant
improvement on the plant performance. The same applies for the output of the FLMC controller, the decision point.

The model of the FLMC control system, comprising the control rules and the values of the linguistic variables, is obtained through an offline intuitive tuning process that starts from a set of the initial insight considerations and progressively modifies the number of linguistic values of the system until it reaches a level of acceptable performance. The design objective is to keep the controller as simple as possible to start with, and only increase complexity, by adding more linguistic values, if required. An adequate number of linguistic values is needed to describe the nonlinear behavior of the system accurately enough. Adding more rules, as expected, increases the accuracy of the approximation, which yields an improved control performance. But beyond a certain point the improvement is marginal.

By choosing the simplest MISO controller, we have avoided the exponential increase of the rule base, and subsequent increase in the complexity of the controller, when the number of input variables increases. The philosophy behind the knowledge base of the FLMC controller is that of being aggressive when the RSSI is low and the Link Loss is high, but on the other hand being able to smoothly respond in the case of adequate conditions in the environment. All other rules can represent intermediate situations, thus providing the control mechanism with a highly dynamic action.

A convenient way to list all possible “IF-THEN” control rules is to use a tabular representation (see Table 13). These rules reflect the particular view and experiences
of the designer, and are easy to relate to human reasoning processes and gathered experiences.

<table>
<thead>
<tr>
<th>decision point</th>
<th>Link Loss Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td>RSSI L</td>
<td>LM</td>
</tr>
<tr>
<td>RSSI M</td>
<td>LM</td>
</tr>
<tr>
<td>RSSI H</td>
<td>L</td>
</tr>
<tr>
<td>RSSI VH</td>
<td>L</td>
</tr>
</tbody>
</table>

Table 13: FLMC Linguistic Rules - Rule Base

5.4.3 Selection of Membership Functions

We further need to quantify the meaning of the linguistic values using membership functions. The membership functions of the linguistic variables are determined by using an intuitive and pragmatic choice and not an analytic approach (this is one of the reported advantages of fuzzy logic controllers compared to the conventional counterparts). The choice of membership function shape is open. Many shapes are often found in studies (see, e.g. [4]). Due to computational simplicity, we select triangular and trapezoidal shaped membership functions in FLMC control system. These types of shapes are a standard choice used in many industrial applications due to the mathematical simplicity of the expressions representing them. The selected membership functions representing the linguistic values for both the inputs and the output of the FLMC controller are shown in Figure 68, Figure 69 and Figure 70. In order to achieve the desired performance, the membership functions are defined based on the real data obtained from long-term testbed evaluation and based on the characteristics of the underlying system. Specifically, the operating regions —

\(^{1}\text{low (L), low-medium (LM), medium (M), high (H), very high (VH)}\)
state partitions are defined based on the observations made of the influence of the two linguistic inputs on attempting to predict the End-to-End loss (as discussed in – Section 4.10 and shown in Figure 64).

Figure 68: RSSI Linguistic Input

Figure 69: Link Loss Linguistic Input

Figure 70: decision point Linguistic Output
The amount of overlapping between the membership functions’ areas is significant. The left and right half of the triangular membership functions for each linguistic value is chosen to provide membership overlap with adjacent membership functions. Our method is simple in that the sum of the grade of membership of an input value, concerning the linguistic values of a specific input variable, is always one (see Eq. (12)).

\[ \sum_{k=1}^{m} \mu_k(x) = 1 \]  \hspace{1cm} (12)

where \( \mu_k(x) \) is the membership value of the input value \( x \) taken from the membership function of the linguistic value \( k \), \( (1 < k < m, \text{where } m \text{ is the number of linguistic values of a linguistic variable}) \), of the input variable of concern.

This results in having at most two membership functions overlapping, thus no more than four rules will be activated at any given time., an approach successfully adopted by other researchers. This offers computational simplicity on the implementation of the FLMC controller, a design objective. The overlapping of the fuzzy regions, representing the continuous domain of each control variable, contributes to a well-behaved and predictable system operation; thus the fuzzy system can be very robust.

The nonlinear control-decision surface implemented by the FLMC controller is shaped by the constructed rule base and the linguistic values of the inputs and output variables (see Figure 71).
This surface represents in a compact way all the information in the fuzzy controller. An inspection of this nonlinear control surface and the linguistic rules shown in Table 13 provides hints on the operation of FLMC. The decision point behaviour under the region of equilibrium (i.e., where RSSI is high and Link Loss is low) is smoothly calculated. On the other hand, the rules are aggressive by increasing the decision point sharply in the region beyond the equilibrium point, where the quality starts to get affected and triggering of handoff is required. The dynamic way of calculating the decision point by the inference process comes from the fact that according to the instantaneous values of the RSSI and Link Loss, a different set of fuzzy rules and so inference apply. Based on these rules and inferences, the decision point is expected to be more responsive than other conventional solutions, (as for e.g. [78]) due to the human reasoning and the inbuilt non linearity.

It is worth remarking that:
1. We have not attempted to optimally tune our fuzzy controller as this can be very demanding (due to the many degrees of freedom associated with the membership functions, the rule base, and the parameters thereof), but more importantly since further tuning beyond the basic intuitive ideas provides limited returns, as the fuzzy controller performs adequately, as demonstrated in Section 5.5.

2. In terms of robustness, we have investigated the stability of the proposed system in terms of phase plane analysis. Based on this technique, we show that the states of the system remain within specific bounds (more later, see – Section 5.6).

3. There is no need for a FIE to be built in each sensor MN, thus saving on memory requirements. After the linguistic rules have been found and the linguistic values are defined, the control surface is known and can be stored as a lookup table (size of $n \times n$) for selected sampling points requiring only a few kilobytes of memory in a fuzzy-capable sensor mobile node. In the system examined $n$ is equal to 25, therefore the lookup table has 625 possible combinations of values. In that way, the memory and computation limitations of sensor networks are taken into account.

Given the above remark, it is thus acceptable to keep the fuzzy inference process as is; however, adaptive tuning of the trigger decision threshold to investigate the tradeoff between increased complexity and improved performance is worthwhile and it can be a subject of future research.
5.5 Performance Evaluation

This section presents the performance evaluation of the proposed FMLC system. At a first stage, we evaluated the selection of the $P_{\text{Threshold}}$ value and then we proceeded with the evaluation of the proposed solution using the refinery testbed.

5.5.1 Evaluation of Threshold ($P_{\text{Threshold}}$)

The output of the fuzzy controller is a decision point which, compared to a predefined threshold, indicates whether the MN will initiate the handoff procedure or not. The fuzzy controller, as explained in Section 5.4, produced a decision point value for the different input parameters. Those probabilities are stored to a lookup table. The mean decision point value based on this table is equal to $P_d = 0.23$. In this section, we will use different values for the threshold in order to identify the most appropriate threshold to use. We start using $P_{\text{Threshold}} = 0.23$ and then we increase/reduce it accordingly. We used the COOJA simulator with the parameters that are shown in Table 14.

<table>
<thead>
<tr>
<th>Table 14: Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
</tr>
<tr>
<td>Testbed Size</td>
</tr>
<tr>
<td>Transmission Range</td>
</tr>
<tr>
<td>Number of simulations</td>
</tr>
<tr>
<td>Number of fixed/mobile nodes</td>
</tr>
<tr>
<td>Mobility model/Waypoint paths</td>
</tr>
<tr>
<td>Packet Rate</td>
</tr>
</tbody>
</table>

Figure 72 shows the End-to-End packet loss for different thresholds. We observe that, for low thresholds, the packet loss is minimized. This is due to the fact that when the threshold is low the MN will be for a longer period of time in scanning...
mode therefore there is a bigger probability to find a better attachment point. This is exactly what happened when we used the Link Loss triggering with low threshold (see Chapter 4).

![Packet Loss using different $P_{\text{threshold}}$](image1)

Figure 72: Packet Loss using different $P_{\text{threshold}}$

Figure 73 shows the average number of triggers. We see that the number of triggers is exponentially increased as the threshold is decreased.

![Number of Triggers using different $P_{\text{threshold}}$](image2)

Figure 73: Number of Triggers using different $P_{\text{threshold}}$
Figure 74 shows the average number of handoffs occurred during the evaluation of the different thresholds. We observe that the handoffs are proportional to the number of triggers, as was expected.

![Figure 74: Number of Handoffs using different P_{Threshold}](image)

Finally, Figure 75 shows the average power consumption for the different threshold values. We observe that for the two low threshold values (P_{Threshold} = 0.06 and P_{Threshold} = 0.16) the power consumption is relatively higher compared to the other threshold values. Again, as in all other evaluations, the power consumption is proportional to the number of triggers and hence to the scanning period duration.

Figure 76 shows the most important metric for the triggering options, the on-time triggering. As we see, the P_{Threshold} = 0.06, P_{Threshold} = 0.16 and P_{Threshold} = 0.18 thresholds show high on-time triggers compared to the other thresholds.
Based on the $P_{\text{Threshold}}$ evaluation, we concluded that the best performance is achieved using a $P_{\text{Threshold}} = 0.16$. The issue of increased power consumption using this threshold could be solved by increasing the free available positions or by minimizing this scanning mode duration.
5.5.2 Refinery Evaluation

To evaluate the proposed FMLC algorithm, a number of refinery experiments were performed. Similar to the evaluation of the RSSI-based decision, the MN was introduced in the refinery testbed area and followed different random walks. We use $P_{\text{Threshold}} = 0.16$ as the threshold value. The duration of the random walks were around 20 minutes. The results show the average of ten different walks in the testbed area.

5.5.2.1 Handoff Decision

At the beginning of each TDMA MAC epoch, the proposed fuzzy based mobility controller finds the current probability value of the trigger decision. If this value is above the triggering decision threshold, the MN will set its idle slots to scan mode in order to start searching for a better attachment point. For the refinery evaluation, the handoff occurs if the following condition is met:

\[
S = \{P_j | ([S_N(k) > S_{\text{thresh}}] \cap [S_N(k) > S_P + \text{hyst}]) \\
\quad \cup ([S_P < S_{\text{thresh}}] \cap [S_N(k) > S_P + \text{hyst}])\} \tag{13}
\]

where $S$ is the set containing possible new attachment points, $P_j$ is the possible new attachment point, $S_N(k)$ is the received signal strength from the new attachment point, $S_{\text{thresh}}$ is the threshold value, $S_P$ is the received signal strength from the parent node and $\text{hyst}$ is the hysteresis value. It is assumed that the hysteresis is equal to one.
In case there is more than one new attachment point meeting the above condition, then the selection of the best available choice is based on the following formula:

\[ \alpha \times RSSI_{last} + \beta \times hops + \gamma \times free \text{ positions} \]  

(14)

where \( hops \) is the distance from the sink node and \( free \text{ positions} \) is the number of free positions that the possible new parent has. Based on prior experimentation, the values were set to \( \alpha = 0.4, \beta = 0.4, \gamma = 0.2 \).

5.5.2.2 Results

Figure 77 shows the operation of the Fuzzy Logic-based Mobility Controller in a representative experiment.

The behavior of the RSSI, Link Loss, and End-to-End Loss was captured in order to conclude if FLMC managed to decrease the packet losses after the triggering was initiated. Based on Figure 77 two handoff events occurred during the experiment. The first handoff, named Handoff 1, occurred when the RSSI value was equal to -80dB and the link loss was equal to 18%. As it is observed, after the trigger and the Handoff 1 event the End-to-End packet loss kept decreasing. Despite that, after a short period of time the End-to-End loss increased again, something that led to a new handoff event, named Handoff 2. The RSSI value during the second handoff was equal to -82dB, where the link loss value was equal to 12%. It is important to note that even though the link loss percentage is lower in this case, the RSSI value is also lower and their combination creates sufficient conditions for a handoff. After the second handoff event, the packet loss had a decreasing trend again.
The proposed FLMC solution was developed based on decentralized information without having any global knowledge about the network condition. Therefore, the decision to handoff or not was based on locally available information that the MN had at the specific time and it could not predict future losses or disconnections. Thus, the performance of the proposed solution can only be determined regarding the packet loss metric, based on the ability to decrease the packet loss after a handoff event and to decrease the total average packet loss comparing to other solutions, like RSSI threshold based ones. Furthermore, a handoff triggering may not result in a re-attachment either because no attachment point exists in the node’s vicinity, or because the possible new attachment points do not have performance qualities which
satisfy the controller’s requirements. In addition, in a number of experiments, it was observed that there are cases at the beginning of the tests where an unnecessary handoff may occur. This is due to the fact that a loss, while not many packets have been sent to the link, indicates a high Link Loss percentage and wrongfully leads to a handoff. This observation was used to add a delay margin for trigger and handoff at the beginning of each test.

The main advantage of the fuzzy based mobility solution, compared with the RSSI threshold-based solution, is that it manages to decrease the average End-to-End packet loss to 2.45%. Figure 78 shows the comparison of the mobility solutions.

![Figure 78: Average End-to-End Packet loss Comparison](image)

It is obvious that in the case of no mobility management (No Handoff) and in the case of the RSSI threshold-based solution the packet loss is high. This is due to the unpredictability of the environment and the RSSI behaviour. On the other hand, using the fuzzy mobility solution, those effects were reduced and a packet loss value within the 3% limit was achieved. Figure 78 shows the breakdown of
the causes of packet loss. The losses are distinguished into two categories: the first category is when the MN has the ability to communicate with the parent node but some communication (bad link) or system losses occurred, and the second category is when the node is located in an area where it is not covered by the communication range of any other node (downtime). The majority of the losses in all cases are due to the system or bad links. On the other hand, the existence of packet losses that occurred due to uncovered areas provides a hint that a better placement of the fixed nodes in the network or the addition of more fixed nodes could help in minimizing the packet loss.

Further to the End-to-End packet loss, Figure 79 shows the power consumption comparison of the mobility solutions.

![Power Consumption Comparison](image)

Figure 79: Power Consumption Comparison

It is clear that both solutions consume more power compared with the scenario where the MN is moving in the testbed without mobility management. This is due to the fact that in order to find a better position more scanning slots are required.
Comparing the two mobility solutions, one can observe that the fuzzy solution performs better than the RSSI threshold solution with a total power consumption decrease of 10.78%. The reason of that, is the fact that the fuzzy solution performs fewer triggers and therefore has less scanning slots. In addition, it is worth noting that the transmission power consumption of the RSSI threshold based solution is increased compared with the fuzzy based solution. This is due to the fact that the increased packet loss leads to more retransmissions of data packets.

The total power consumption was calculated considering the following power elements: Transmission power (Tx), Reception Power (Rx), Flash Write Power (Fr), Flash Read (FR), CPU Active (CPUact) and CPU Sleep (CPUsl).

Based on [79], the radio and external flash device have significantly higher power consumption than the microcontroller. The flash consumes power only when the microcontroller writes to or reads from the flash. Similarly, the radio consumes power only when the radio is transmitting or listening. The most important thing to note is that the radio consumes a significant amount of power when it is listening for radio traffic. Using the results shown in Figure 79 the reception power contributes up to 90% to the total power consumption. Therefore, it is crucial to minimize reception slots. A solution to this overhead could be an adaptive way of selecting the threshold value. In such way, the adaptive thresholding module will use information from the network performance in order to adapt accordingly the threshold. For example, since there is not any guarantee that the MN will manage to find a better attachment point during scanning mode, the adaptive module could record the number of scanning
slots and if these slots are above a predefined value it will force the MN to exit scanning mode. To gauge the impact on lifetime, if one were to assume the use of standard 3000 mAh batteries, the MN would have a life expectancy of 175 days.

Moreover, based on Figure 80 the fuzzy mobility solution has increased the effective triggers (ratio of successful handoff triggers) from 4.15% to 8.1% by decreasing, at the same time, the average total number of triggers from 108.5 to 18.5. The reduction of the unnecessary triggers leads to the reduction of the power consumption.

Furthermore, the packet delivery delay of both mobility solutions (Figure 81) is inside the limit of 1 second, whereas in the case where there is no mobility management this delay is over 1 second. The reason is that the packets are kept in the queue for a longer period of time due to the fact that the MN could be outside the transmission range of its parent node.

Concluding, it is obvious that the fuzzy logic based mobility solution performs better in comparison with the RSSI-based mobility solution, and it fulfils some basic
performance requirements that were set for the specific application environment (e.g. End-to-End packet loss less than 3% and an End-to-End delivery delay of no more than 1 second).

5.5.3 Overall Evaluation

Table 15 presents an overall comparison of the Fuzzy Logic-based solution with the single-based solutions in terms of End-to-End packet losses, power consumption and on-time triggering. The first important observation is that the Fuzzy Logic-based solutions on average have higher on-time triggering percentage which means that we can consider Fuzzy Logic-based triggering as the best triggering solution. The second important observation is the fact that the Fuzzy Logic-based solution with $P_{threshold} = 0.06$ shows the minimum End-to-End packet loss and the higher on-time triggering percentage. Despite that, compared to the majority of the other solutions it shows increased power consumption. However, compared to the Link Loss solution with threshold 1% it presents 42% less power consumption. The
common characteristic of both solutions is the low threshold values. Based on these observations, the next step will be to find a way to minimize the power consumption overhead of the fuzzy-based solutions. This could be achieved by implementing an adaptive way to select the threshold value based on the current behaviour of the system. Therefore, we consider that even the specific $P_{\text{threshold}}$ thresholds, shown in Table 15, present a better performance compared to the other solutions, an adaptive threshold selection would improve the performance more and especially in decreasing the power consumption and increasing the on-time triggering.

Table 15: Experimental Results

<table>
<thead>
<tr>
<th>Solution</th>
<th>Packet Loss [%]</th>
<th>Total Power Consumption [mW]</th>
<th>On-time [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSSI Threshold, -78dBm</td>
<td>4.1</td>
<td>0.39</td>
<td>32.4</td>
</tr>
<tr>
<td>EWMA RSSI, $t = 5, a = 0.33$</td>
<td>3.47</td>
<td>0.368</td>
<td>17.92</td>
</tr>
<tr>
<td>SMA RSSI, $n = 10$</td>
<td>3.45</td>
<td>0.37</td>
<td>22.2</td>
</tr>
<tr>
<td>Link Loss, Threshold 1%</td>
<td>2.42</td>
<td>3.11</td>
<td>45.3</td>
</tr>
<tr>
<td>EWMA Link Loss 10%, $t = 5, a = 0.33$</td>
<td>2.41</td>
<td>0.79</td>
<td>21.6</td>
</tr>
<tr>
<td>SMA Link Loss 10%, $n = 10$</td>
<td>2.43</td>
<td>0.85</td>
<td>38.9</td>
</tr>
<tr>
<td>Fuzzy, $P_{\text{threshold}} = 0.06$</td>
<td>2.1</td>
<td>1.8</td>
<td>61.4</td>
</tr>
<tr>
<td>Fuzzy, $P_{\text{threshold}} = 0.16$</td>
<td>2.4</td>
<td>1.3</td>
<td>54.2</td>
</tr>
<tr>
<td>Fuzzy, $P_{\text{threshold}} = 0.18$</td>
<td>2.5</td>
<td>0.66</td>
<td>39.4</td>
</tr>
</tbody>
</table>

5.6 Phase Plane Analysis

Our objective has been to control the handoff procedure in order to choose the attachment point, which ensures low End-to-End packet losses. Based on the plot of Figure 64 low End-to-End packet loss can be achieved by minimizing the link loss.
and maximizing the RSSI. The considered control system was shown schematically in Figure 67.

It can be observed that the Fuzzy Logic Controller provides the switching logic, which at any time chooses the “best” attachment point in the sense that it is the one that minimizes the Link Loss and increases the RSSI. The output of the fuzzy controller is a value that when compared with a predefined threshold indicates whether the MN will initiate the triggering procedure. When the triggering starts, the MN will search for a new attachment point. It will decide to handoff if the new attachment point (if any) fulfills the handoff criteria. Stability analysis of the proposed control system is difficult due to the complexity of the considered plants, which makes the modelling procedure intractable. The absence of a validated model of the plant has motivated our fuzzy control design. Since investigation of the stability is intractable using mathematical model analysis, we use phase plane analysis, which is common in similar cases. We consider the RSSI and the Link Loss to be the states of our system and we construct plots of RSSI versus the Link Loss using simulations. Due to the inherently random nature of the system, it does not converge to a single equilibrium point. However the states of the system remain within specific bounds. In Figures 82 and 83 we show plots of the RSSI versus the Link Loss with and without the FLMC.

We observe that in both cases the states remain bounded with minimum value equal to 0% and maximum value equal to 50%. Since stability in terms of boundedness of the considered signals is achieved in both cases, the benefit gained from using
the FLMC is that the controlled system increases the probability of operating in a region, which ensures high RSSI and low Link Loss values which has been our initial objective. This is evident in Figures 82 and 83, which demonstrate that when the FLMC is used, areas with low Link Loss and high RSSI are more densely populated. In order to make this even clearer, we plot density histograms of the Link Loss and RSSI values in the case of the controlled and the uncontrolled systems, which are shown in Figures 84, 85, 86, 87. We observe that the use of the FLMC controller...
manages to increase the density of the low Link Loss values and, at the same time, increases the density of the high RSSI values.

![Link Loss Histogram with FMLC](image1)

**Figure 84: Link Loss density with FLMC**

![Link Loss Histogram without FMLC](image2)

**Figure 85: Link Loss density without FLMC**

The non-zero density values at high link loss values are due to the fact that there is not any guarantee that the MN will manage to find a new attachment point to handoff. In such a case, the MN will show increased losses.

In addition to the above, Table 16 depicts statistics of the Link Loss that support the claim that FLMC managed to operate in regions with lower Link Loss and higher...
RSSI than other system. As we can observe, the mean value in case where the FLMC is not used, is 11.4%, whereas is the case where the FLMC is used, then the value is 6.05%. In addition, the FMLC system presents lower standard deviation.

Regarding the RSSI, it can be observed that in Table 17 the FLMC managed to operate in higher regions, something which is evident by the mean and standard deviation statistics.
Table 16: Link Loss Statistics Comparisons

<table>
<thead>
<tr>
<th>Solution</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Median</th>
<th>st. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLMC</td>
<td>0</td>
<td>50</td>
<td>6.05</td>
<td>3.1</td>
<td>7.8</td>
</tr>
<tr>
<td>Without FLMC</td>
<td>0</td>
<td>50</td>
<td>11.4</td>
<td>7.1</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Table 17: RSSI Statistics Comparisons

<table>
<thead>
<tr>
<th>Solution</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Median</th>
<th>st. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLMC</td>
<td>-89</td>
<td>-37</td>
<td>-57</td>
<td>-54</td>
<td>7.6</td>
</tr>
<tr>
<td>Without FLMC</td>
<td>-89</td>
<td>-37</td>
<td>-64</td>
<td>-65</td>
<td>9.85</td>
</tr>
</tbody>
</table>

5.7 Evaluation using different Physical Topology

The node placement in the refinery testbed was performed using a deterministic deployment, where sensors were precisely placed at pre-engineered positions capable to provide acceptable communication quality. When the network is consisted of a small number of nodes, this deterministic approach is preferred since one can easily determine whether the network is connected, and if not, to add relay nodes where needed. On the other hand, when having a large number of nodes, it is preferred to deploy the nodes randomly in order to reduce installation costs. Eve though our networks consisted of a small number of nodes, we decided to also use a randomly deployed topology in order to compare the proposed solutions.

Therefore, we repeated the experiments using two more new topologies. The first topology is the randomly constructed topology. For the second topology, we used the basic refinery topology with small changes in the placement of some nodes. The purpose of this kind of evaluation is to observe whether the proposed solutions depend on the underlined topology or not and how they perform under different
topologies. It should be mentioned that, since we have different placement/topology, we can not compare the same solutions between them (ex. Fuzzy with $P_{threshold} = 0.16$ using the basic topology with the Fuzzy with $P_{threshold} = 0.16$ using the similar topology) because a different topology means different logical tree and therefore, different experiment. Hence, what we want to observe is if the different solutions behave the same under different topologies. For example, is the packet loss of Fuzzy Logic-based solution with $P_{threshold} = 0.16$ less than the RSSI threshold solution in random topology as it happens in refinery topology?

Figures 88, 89 and 90 show the different topologies that were used. In the refinery placement we observe that the nodes were placed in the center section of the testbed with small distances between them. In the refinery-modified topology, the nodes were once again placed in the center section of the testbed but distributed to a bigger area. Finally, in the random topology, the nodes were mostly placed near the sink node.

![Figure 88: Physical Refinery Placement](image)
5.7.1 Random Topology

Instead of using a deterministic placement, we proceed with a random placement of the nodes (Figure 90). We repeated the experiments five different random placements and Figure 95 shows the results regarding the End-to-End packet loss. As we observe, in all cases, the losses have increased. This is due to the fact that the random placement of few nodes creates uncovered areas, therefore in these areas
the MN communication is disconnected. In addition, since in the specific placement the majority of the nodes are next to the sink node, the constructed logical tree will not provide free available position in the sink nearby areas.

![Packet loss Random vs Refinery Placement](image)

**Figure 91: Packet loss Comparison of Refinery vs Random Placement**

Figures 92 and 93 show the total number of triggers and handoffs respectively. Using the random topology, the triggers are increased in all cases. In addition, we observe that the handoffs are also increased in all the solutions with the single-based solutions to show the highest increment. This is mostly due to the higher trigger increment of the single-based solutions which lead to more scanning/receiving period and therefore to higher probability to handoff.
Finally, Figure 94 shows the total power consumption of the solutions. We observe that, using the random placement, the power consumption is increased in all the solutions as a consequence of the increased number of triggers and therefore there is an increased scanning/receiving period.
Comparing the overall performance of the different solutions using both placements we observe that the behaviour is the same. For example, in both placements the Fuzzy-based solutions outperform the RSSI-based in terms of packet losses.

### 5.7.2 Refinery Modified Topology

As mentioned above, the second topology that we used is similar to the refinery topology with small changes to the placement of some nodes. The reason of these small changes is to maintain the connectivity and avoid the creation of “black holes” in the communication of the sensor nodes. Our approach for the changes was to keep the nodes placement in the center of the testbed but with larger distances between them.
Figure 89 shows the node’s modified refinery placement. Using the same simulations parameters, we performed the experiments and the results are shown in Figures 95, 96, 97 and 98.

As we can see, the refinery-modified placement outperforms the refinery placement in all evaluation metrics. This is due to the better distribution of the nodes in the center of the testbed.

![Packet loss for different Pd](image)

Figure 95: Packet loss Comparison of Refinery vs Refinery Modified Placement
Figure 96: Number of Triggers Comparison of Refinery vs Refinery Modified Placement

Figure 97: Number of Handoffs Comparison of Refinery vs Refinery Modified Placement
5.8 Evaluation with more free tree positions

One of the major issues of the handoff procedure is the discovery of a new attachment position that could provide a better performance than the existing attachment point. Up until now, in our evaluation settings, we had two free available positions something that could potentially affect the handoff procedure. In order to discover the importance of the free available position, we removed one fixed node from the network and repeated the simulations using the same parameters as in previous evaluations.

Figure 99 shows the comparison of the experiments using two and three free positions. As we can see, in case of three free positions the End-to-End packet loss is reduced in all cases. The higher gain is shown in the case of LL=1% (up to 40%) with the Fuzzy-based solutions of $P_{\text{threshold}} = 0.16$ and $P_{\text{threshold}} = 0.18$ to follow with 33% and 27% respectively.
Figure 99: Packet Loss comparison of free available positions

Figure 100 shows the power consumption of the different cases. It is clear that when having more free positions to attach the power consumption is reduced. The highest reduction is equal to 17% and it is observed in case of $P_{\text{threshold}} = 0.18$, where in case of $P_{\text{threshold}} = 0.16$ the reduction is equal to 13%. Comparing Figures 99 and 100 we conclude that even the LL=1% produced the highest gain in packet losses, this was done with no gain in power consumption. This is actually explained from the fact that using LL=1%, in the majority of the operation time, the MN is in scan mode, therefore, will continuously search for a new attachment point. So, when having more free attachment points, the MN will find a better connection with increased probability. On the other hand, the Fuzzy Logic-based solutions managed to reduce both the packet losses and power consumption. This mainly relates to the fact that Fuzzy Logic-based solution present the highest on-time handoff value.
Figure 100: Power Consumption comparison of free available positions

5.9 Comparison of different Radio models

The proposed FMLC was designed based on the radio propagation model of the refinery environment. In addition to that, in this section we will use a simplified and different radio propagation model where the RSSI linearly depends on the distance between the transmitting and receiving node. This radio propagation model is the default model of COOJA simulator and it is called Unit Disk Graph Medium (UDGM): Distance Loss. The UDGM abstracts radio transmission range as circles. It uses two different range parameters, one for the transmissions and one for the interfering with other radios and transmissions; both radio ranges grow with the radio output power indicator. In our experiments, by using the distance based solution we set transmission/reception success equal to 1, which means that if two
nodes are within the communication range of each other the packet will be delivered with a 100% success.

Figure 101 shows the packet losses comparison of the distance based model and the refinery model. As we observe, the distance based provides fewer losses compared to the refinery model. The highest improvement is shown in the case of the RSSI Threshold solution. The reason for this is the absence of the RSSI fluctuations and the 100% delivery success, if the nodes are within communication range. Comparing the mobility solutions we observed that again the Fuzzy-based solution performs better in terms of packet lost than any other solution.

![Packet Loss comparison of different Radio Propagation Models](image.png)

Figure 101: Packet Loss comparison of different Radio Propagation Models

Figure 102 and 103 show the number of triggers and the number of handoffs for both radio propagation model. It is obvious that in the case of the Fuzzy Logic-based solution we have less triggers compared with the other solutions; that is, the proposed Fuzzy Logic-based solution controls the handoff triggering procedure better.
compared to the conventional solutions, by minimizing the number of unnecessary handoffs. This is due to the fact that the Fuzzy Logic-based solution is not solely affected by a single-based metric behaviour.

Figure 102: Triggers comparison of different Radio Propagation Models

Figure 103: Handoff comparison of different Radio Propagation Models
Finally, Figure 104 shows the power consumption comparison. We observe that, in Fuzzy Logic-based solutions the power consumption is drastically reduced when using the distance-based radio propagation model. This is because of the smaller duration of the triggering periods since in distance-based model the input parameters of the FMLC (RSSI and Link Loss) change frequently compared to the refinery (Gaussian-based) model. Therefore, the FMLC can exit from scanning mode easily. In addition, we observe that the power consumption of the RSSI-based solution is increased because of the increased triggers. Finally, power consumption of the Link Loss triggering solutions is reduced mainly due to the different link loss formulation where, in case of the refinery, it is based on the equation 6 (Figure 22) and, in case of the distance-based it is based on the transmission range (100% success reception if within the range and 0% success if out of range).

![Power Consumption comparison of different Radio Propagation Models](image)

Figure 104: Power Consumption comparison of different Radio Propagation Models
5.10 Evaluation using different Packet Rates

In this set of experiments, we have changed the application packet rate from 1 packet per 3 seconds to 1 packet per second in order to conclude if the packet rate affects the overall performance. We performed 100 experiments and the results are shown in Figure 105, Figure 106, Figure 107 and Figure 108.

Based on the results, it is clear that the higher data rate does not affect the operation of the mobility solutions since in all the metrics the results are close to the lower packet rates results. The only remarkable point is the fact that in case of higher packet data rates (ex. 1 packet per second) the total power consumption is increased. This is due to the increased number of packet transmissions.

![Packet loss for different Packet Rates](image)

Figure 105: Packet Loss comparison of different Packet Rates
Figure 106: Triggers comparison of different Packet Rates

Figure 107: Handoff comparison of different Packet Rates
5.11 Evaluation using different Mobility models

In order to identify how the different mobility models affect the overall performance, we repeated the experiments using two different mobility models, the Gauss Markov and the Manhattan Grid models. For the Gauss Markov model, we set the maxSpeed= 3m/s and the speedStdDev= 0.5. For the Manhattan Grid model, we set the grid size to 10x10, the minSpeed=0.5 m/s, and the meanSpeed=1.5.

We performed 100 experiments and the results are shown in Figure 109, Figure 110, Figure 111 and Figure 112.
Figure 109: Packet Loss comparison of different Mobility Models

Figure 111: Handoff comparison of different Mobility Models
It is obvious that Random Waypoint model shows better performance. This is due to the characteristic of Random Waypoint model to cluster the nodes near the centre region of simulation field and move away from the boundaries (density wave phenomenon). Observing the nodes’ placement, we see that the center region of
the testbed area has higher node density than the boundaries. Furthermore, based on [80] the Random Waypoint model provided the maximum connectivity (close to 90%) among the nodes for low density networks compared to the Gauss-Markov (close to 70%) and Manhattan Grid (close to 65%) models. Thus, Random Waypoint model present lower packet losses due to connectivity issues compared to the other two mobility models.

5.12 Evaluation using different Trees and number of Nodes

A new set of experiments was performed in order to identify how different tree structures and number of nodes affects the overall performance of the system. We selected the new trees to be the 4-2-1 (Figure 113) tree which supports in total 21 nodes compared to 16 nodes supported by the 3-2-1 tree, and the 3-2-1-1 tree which supports in total 22 nodes.

Figure 113: 4-2-1 Tree Topology

In these experiments, we considered two different scenarios. In the first scenario, we used the 4-2-1 and 3-2-1-1 trees with the same number of nodes and the same
placement as in case of the 3-2-1 tree, meaning 13 fixed nodes and one MN with the refinery placement. Therefore, this scenario provides more free positions for the MN to handoff. In the second scenario, we used the 4-2-1 and 3-2-1-1 trees with 17 and 18 accordingly fixed nodes and one MN. For the 13 fixed nodes we had the same placement as in the refinery topology and the 4 or 5 new nodes were randomly distributed in the testbed area. This scenario provides higher connectivity due to the extra nodes than the 3-2-1, 4-2-1 or 3-2-1-1 scenarios with 14 nodes.

At a first stage, we evaluated the 4-2-1 tree. Regarding the packet losses as shown in Figure 114, we observed that both scenarios using 4-2-1 tree provide fewer losses compared to the basic 3-2-1 tree scenario. This is explained in two ways: in case of 4-2-1 tree with 18 nodes the reduction is due to the connectivity improvement that was achieved by the 4 randomly placed nodes, where in case of the 4-2-1 tree with 14 nodes the reduction is due to the extra attachment positions, which means that the MN can easier find a new better attachment point to connect.
Figure 114: Packet Loss comparison of different Tree and Nodes

Figure 115 shows the total number of triggers. We see that the number of triggers in case of 4-2-1 scenarios is bigger compared to the 3-2-1 basic scenario. This is due to the fact that the triggers led to increased number of handoffs and therefore the MN is not continuously (using the same trigger) searching for a new attachment point. Despite that someone could claim that this could be a drawback, observing Figure 117 we conclude that 4-2-1 could have more triggers but the scanning duration is smaller since it has more free positions or better placement, therefore the power consumption is less.
Figure 115: Triggers comparison of different Tree and Nodes

In Figure 116, we observed the total number of handoffs where both scenarios using 4-2-1 present higher number of handoffs. Again, this is due to the extra free positions and to the better coverage of the testbed area.

Figure 116: Handoff comparison of different Tree and Nodes
Finally, Figure 117 shows the total power consumption where we can see that, in general, the power consumption of both 4-2-1 tree scenarios is less compared to the 3-2-1 basic scenario. This is due to the fact that in 3-2-1 basic scenario the scanning periods are longer since the MN has less free positions and worst coverage than the 4-2-1 tree scenarios. Concluding, based on the results presented in this sub-section, we can assume that the different mobility solutions are not affected by the different tree structure or larger number of nodes since the performance comparison between them is the same, fuzzy logic performs always better than any other solution. Despite that, it is clear that a tree with more free positions or a scenario with more nodes that provide better coverage will lead to an improved performance.

![Power Consumption for different Trees and Number of nodes](image)

Figure 117: Power Consumption comparison of different Tree and Nodes

The second stage includes the evaluation of 3-2-1-1 tree. Figures 118, 119, and 120 show the packet loss, the number of triggers and the handoffss occured. Based on
these figures, we can extract the same conclusion as in case of 4-2-1 tree: the performance of MN in terms of packet lost is improved when we provide a better coverage of the physical area and an increased number of available attachment points. This statement was proven using trees with different depth and width.

Figure 118: Packet Loss comparison of 3-2-1-1 Tree and different number of Nodes

Figure 119: Triggers comparison of 3-2-1-1 Tree and different number of Nodes
5.13 Execution Overhead Comparison

In this section, we present the overhead of Fuzzy Logic-based solution in terms of code size and execution time compared to other triggering solutions.

The first metric relates to the number of bytes which is needed to implement each of the triggering solutions. The overall target regarding the code size was to manage to implement all the possible triggering solutions as part of the overall system implementation. The hardware that we used was the TelosB which has flash memory equal to 48KB (49152 bytes).

Figure 121 shows the total number of bytes of the system implementation using different triggering solutions. As we observe, all the solutions remain below the limit of 48KB. Comparing the mobility code size, we observe that the Fuzzy Logic-based solution requires 808 bytes, RSSI threshold requires 50 bytes, Link Loss requires 330
bytes, SMA using RSSI requires 396 bytes and finally SMA using LL requires 358 bytes.

![Figure 121: System Code Size per Solution](image)

During the initial setup of the system we assigned 2 slots (10ms per slot) for any kind of calculation that needed to be performed. Figure 122 shows the execution time of the mobility code.

We see that the Fuzzy Logic-based solution results the highest execution time which is around 5 times more than the RSSI-based solution and 3-4 times more than the other solutions. In addition, all the mobility solutions are within the time limits of the 20ms. Despite all these, the Fuzzy Logic-based solution resulted in a better way of controlling the handoff procedure, therefore any execution overhead is minimized due to the positive effects of the Fuzzy Logic-based solution.
5.14 Adaptive FMLC

Based on the results presented until now, it is clear that the use of Fuzzy Logic-based triggering outperforms any other triggering option. The only point that someone can argue about the performance of the Fuzzy Logic-based solution is the power consumption which in some cases is increased. In order to minimize the power consumption, we must first identify the reason of this behaviour. Using the “problematic” scenarios regarding the refinery environment, we observe that the reason of the increased power consumption was the long scanning period in some scenarios where the node did not manage to find a new attachment point. The way of initiating and terminating the scanning mode is critical. For example the lowest power consumption is appeared using the RSSI-based solution. The reason for this is the overall behaviour of the RSSI since the trigger is terminated as easily as it is initiated. Therefore, although this solution presents high number of triggers, the
duration of the scanning period is small, hence the power consumption is low. On the other hand, the Link Loss triggering shows the exact opposite behaviour since it triggers the handoff fewer times but the duration of scanning period is high (especially when the threshold is low (1%)). Finally, the Fuzzy Logic-based solution presents in the 60% of the scenarios, low power consumption where in the remaining scenarios the power consumption is high. In order to solve this issue, we optimize the FLMC using adaptive thresholding, meaning that we adaptively change the $P_{\text{threshold}}$ during running time instead of having a fixed value, which was the case until now. The implementation and the operation of the adaptive functionality must be kept as simple as possible so that to avoid extra overhead on the system operation. In order to adapt the $P_{\text{threshold}}$, we selected two metrics where the first relates to the scanning duration and the other relates to the burst losses. The meaning of the first metric is to increase the $P_{\text{threshold}}$ when the MN operates in scanning mode for $x$ continues epochs and the meaning of the second metric is to decrease the $P_{\text{threshold}}$ when burst losses occur. The second metric could also be used to increase the on-time triggering. Figure 123 shows the modified FLMC system after the addition of the adaptive thresholding module.

In order to evaluate the updated system we set the $P_{\text{threshold}} = 0.16$, the scanning epoch threshold equal to 5 and we assume that we have burst losses if 3 consecutive packet are lost. Algorithm 4 shows the algorithm implemented to adapt the $P_{\text{threshold}}$. 
Algorithm 4 Adaptive Thresholding

if $cont_{\text{scanning}} > 4 \land burst \leq 2$ then
    $P_{\text{threshold}} = P_{\text{threshold}} + 0.01$
else if $burst > 2$ then
    $P_{\text{threshold}} = P_{\text{threshold}} - 0.01$
else
    $P_{\text{threshold}} = P_{\text{threshold}}$
end if

We ran the simulations of the FLMC system with adaptive thresholding using the same simulation parameters as previously. We compared the performance of the adaptive thresholding $P_{\text{threshold}}$ with the performance of the fixed $P_{\text{threshold}} = 0.16$. Figure 124 shows the comparison results. It is observed that using the adaptive feature, the packet loss was reduced by 6% and the power consumption was reduced by 59.6%. In addition, we have a small increment for the handoffs and an increment of 50.4% for the triggers.
In addition to the above, Figure 125 shows the comparison of the on-time triggering. It is obvious that the adaptive thresholding increase the on-time triggering due to its ability to adapt the $P_{\text{threshold}}$ based on the burst losses.

Figure 125: Onetime Triggering Adaptive Thresholding
5.15 Chapter Summary and Conclusions

In this chapter, we designed and implemented a mobility management solution in WSN, to support mobile workers inside an industrial environment. The proposed mobility solution efficiently maintains the connectivity of the mobile node by controlling the handoff procedure. In the design of this solution network state variables are used, which are available by every sensor mobile nodes. Thus, the proposed mechanism is generally applicable to any WSN industrial environment or testbed setting with mobility requirements. This work moves beyond simple single-based mobility solutions by proposing an intelligent controller, based on fuzzy logic, in order to help sensor mobile nodes to control handoffs with a need for performance guarantees. The applicability and operability of the proposed mobility solution was evaluated in a real testbed scenario inside an industrial environment, as is an oil refinery.

The results clearly show that the proposed mobility solution outperforms any single-based mobility solution, in terms of packet loss, power consumption, and on-time triggering. In order to validate the above conclusions, we used COOJA simulator optimized with the refinery radio propagation under different use cases. We evaluated our solutions using the different nodes’ physical placement, different radio propagation models, different size of network, different packet rates, different trees, and different mobility models. In all cases, the Fuzzy Logic-based solution displayed the best performance. We also considered the overhead of the Fuzzy Logic-based solution against the single-based solutions, where we observe that the
overhead added by the implementation and operation of the Fuzzy Logic-based solution within practical memory requirements, and justify the memory overhead in comparison to the gains. Finally, in order to further improve the performance of the Fuzzy Logic-based solution we implemented an adaptive thresholding solution with the main target to reduce the power consumption and to increase the on-time triggering.

It worths to mention that the proposed approach can be used over any underlying architecture since it was designed in a way that requires only the existence of two general metrics, the RSSI and the Link Loss. In our case, we have used the GIN-SENG infrastructure, in order to avoid any inconsistencies and stability problems of the supported infrastructure.
Chapter 6

6LoWPAN Mobility Support

6.1 Introduction

The Internet of Things is an intelligent network for automatic information interaction and processing between things, or between people and things. Things equipped with smart sensors can communicate to other objects through a transmission network. This implies connectivity between anything at anytime, regardless of place, and assumes that overall perception, reliable transmission, and intelligent processing are fulfilled. The Internet of Things services have various definitions and application forms in different industries. For example, a typical concept is to connect things to the Internet by short-distance information sensor devices like RFID in order to fulfil local “smart recognition and management” of the things. Machine to Machine (M2M) services defined by mobile service operators is another narrow definition of the Internet of Things. It specifically refers to interactive communication services between wireless terminal devices (at least one part is a device) that
can automatically implement program controlled communications via cellular mobile communication networks. Both of these definitions incorporate some sort of a gateway to bridge the local (RFID, Mobile Phone) with the global (Internet) technologies. Our definition of the IoT is more general and considers the connectivity of everyday smart mobile devices and embedded system objects (i.e. wireless sensor networks, ambient devices) via the same type of architectures and protocols fuelling and supporting today’s Internet, i.e. the Internet Protocol (IP). The use of IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) is an example of short-range and low cost communication able to support the concept of the IoT. The key in our case is the use of mobile devices/things something which assumes the existence of a proper mobility management under 6LoWPAN technology.

6.2 Related Work

The use of 6LoWPAN, and therefore the use of IP, provides global addressability of the objects something that allows the access to any information, at any specific time, from anywhere. Inside a mobile 6LoWPAN environment there is the possibility for an object to move to another network and consequently the 6LoWPAN address of the object is changed. To deal with such scenarios a suitable mobility management protocol is needed. As presented in Section 2.5 several solutions have been proposed to handle the movement of a MN in IP-based networks. In addition to those solutions, specific solutions that target 6LoWPAN mobility support have been
proposed. The latest draft about mobility in 6LoWPAN [81] identifies the main mobility scenarios, the major challenges and security issues for these types of networks. In addition, a compression scheme about the application of MIPv6 in 6LoWPAN is presented in IETF draft [82]. Kim et al. [22] proposed a compressed packet header format to support the mobility of 6LoWPAN and a Lightweight NEMO protocol to minimize the signalling overhead between 6LoWPAN mobile routers and 6LoWPAN gateways by using a compressed mobility header. To provide mobility for 6LoWPAN nodes, they adopt the Network Mobility (NEMO) protocol. To support mobility headers in 6LoWPAN packets, a new dispatch header pattern is defined, LOWPAN MH, to add a compressed IPv6 mobility header to a dispatch. Kim et al. [83] also proposed an interoperable architecture between NEMO and 6LoWPAN. To accomplish interoperability, they enhanced the routing protocol: An extended LOAD routing scheme for mobile routers to support mobility in 6LoWPAN sensor nodes. Enhanced routing performs default gateway discovery and mobile network prefix discovery operations for packet forwarding, path optimization and backup route maintenance. The drawback of the last two solutions is that they cannot deal with individual node mobility though they are clearly beneficial when applied to mobile 6LoWPANs. Bag et al. in [84] use an adaptation layer packet format for mobility signalling from 6LoWPAN. The proposed mobility supports a mechanism that reduces the Inter-PAN handover time by providing some extra information about the frequencies of the surrounding PANs at the border nodes. The performance evaluation is based on the mobility signalling cost incurred to provide mobility in
the network, which is given by analytical modelling. The results clearly indicated that less signalling (in number of bits) is required, compared to HMIPv6 when the speed and the packet arrival rate of the mobile device increase. A message format of location update (LU) message and data packets is proposed. Finally, Bag et al. [85] presented a network-based intra-mobility scheme for mobile 6LoWPAN nodes in which the mobility of 6LoWPAN nodes is handled at the network side. LoW-Mob ensures multi-hop communication between gateways and mobile nodes with the help of the static nodes within a 6LoWPAN. However, this solution supports only the intra-mobility scenario and requires extra hardware (antennas) in order to obtain the Angle of Arrival (AoA) measurements. In addition, each SN must be equipped with a radio-triggered hardware component that activates sensors from/to their sleep state, by sending a special wake up radio signal.

6.3 Background

The usage of IPv6 technology in tiny low power devices impose some benefits. Those benefits include the easy interconnection with other IP networks, the reuse of existing internet infrastructure, the application of the well-known IP-based technologies to sensor networks and the use of existing power monitoring and diagnostic tools. The industry and in general the end users, can not trust a technology which appeared in the last couple of years and is still not stable, but they want to have a technology that is supported from open long-lived and reliable standards, like the IP. All users want to control those devices via the internet, thus the integration
with IP and the interconnection with the internet will help the users to have an easy learning curve of this technology, as all the users know how to use the internet. Another benefit of the IP usage is the End-to-End communication that the IP can offer. In addition, the infrastructure at End-to-End communication is not involved thus the scalability and maintainability is not affected. The challenge in supporting IP protocols in WSN is to overcome the limitations, that by default, the sensor network encompasses like lower power consumption, low duty cycles, limited bandwidth and reliability.

In order to manage the support of IP in WSNs the 6LoWPAN introduces an adaptation layer between the IP stack link and network layers to enable efficient transmission of IPv6 datagrams over 802.15.4 links, dramatically reducing the IP overhead. The adaptation layer is an IETF proposed standard and provides header compression to reduce transmission overhead, fragmentation to support the IPv6 minimum/maximum transmission unit (MTU) requirement, and support for layer-two forwarding to deliver an IPv6 datagram over multiple radio hops.

6.4 Proposed Solution

In order to support a network-based solution, we introduce an entity called 6LoWPAN proxy agent (PA). The 6LoWPAN PA belongs to the Full Function Devices category. We consider that PA, as an FFD, is a “powerful” device and will typically have more resources and may be mains powered. The use of 6LoWPAN proxy entities is supportive in mobility scenarios in order to reduce the number of
signalling between the MN and the Home Agent. The idea behind this is to force the 6LoWPAN PA to be responsible for MNs mobility signalling and operation with the HA and simply inform the MN, when necessary, to handoff to a new serving proxy (within or outside the same PAN).

Figure 126: Tree-based Communication

When the MN is switched on for the first time, it has to establish L2 connectivity by receiving beacons and associate with a specific channel. After that, it should ran the Neighbor Discovery (ND) procedure to retrieve information from the network, like the network prefix. Finally, the Duplicate Address Detection (DAD) procedure should be run to ensure that the global address obtained by the MN is unique. The DAD procedure should be ran by the backbone Router to unload the MN from time and resource consuming operations. The above three steps can be grouped in one
phase called bootstrapping. During the ND procedure the device is auto-configured and gets a global IPv6 address. The global address is constructed based on the network prefix and the 64-bit interface identifier (IID). In 6LoWPAN networks, it is assumed that the IID has a direct mapping to the link-layer address; as a result address resolution is avoided. Inside each PAN, we use a unique 16-bit address instead of using the IPv6 address. The edge router is responsible to map this 16-bit address to the global IPv6 address, in case there is a need to communicate with a node outside the 6LoWPAN network. This procedure has a strong relationship with security and an appropriate key management option has to be followed. The ND procedure signalling is shown in Figure 127.

![Neighbor Discovery procedure](image)

Figure 127: Neighbor Discovery procedure

In this chapter, we deal with the following two types of mobility (Figure 128):

1. Device movement within a single Wireless PAN domain (Intra-PAN or micro-mobility): This scenario is probably the most common in WSNs architectures.
The sensor node moves within the domain without losing the connectivity with the Sink node (Edge Router).

2. Device movement between multiple Wireless PAN domains (Inter-PAN or macro-mobility): Sensor nodes move between different sensor networks, each one with its Sink node being responsible to configure and manage all the aggregated devices. In this type of mobility, the IPv6 prefix of the network is changed.

Both mobility types described above belong to the category of node mobility, where a single node moves between points of attachment.
6.4.1 Intra-PAN Mobility Scenario

While the MN is moving inside the same PAN the 16-bit short address that is used to reach the node is not changed. In this section, we study the procedure of how the MN parent proxy is changed inside the same PAN.

Our proposed mobility model is based on the following assumptions:

1. 6LoWPAN PAs located in the same network will advertise the same prefix.

2. The address of the MN inside the same network is not changed.

3. The proxy node and MN exchange packets when the MN is bootstrapping.

In intra-PAN case, mobility relates to the selection of a new 6LoWPAN PA. The signalling of the intra mobility scenario is shown in Figure 129.

The steps of the proposed solution are as follows:

1. The 6LoWPAN PA measures the quality of the link with MN using any of the triggering solutions which are proposed in previous Chapters.
2. If the triggering procedure is activated, the current 6LoWPAN PA will inform the surrounding PAs about any MN movement and will instruct them to start hearing for packets from the MN by setting their mode to scan.

3. When the candidate PAs capture packets from the MN, they will create a Join message where in the payload field they will include the MN 16-bit address, PAN ID and the RSSI value of the message that they captured. This message will be sent to the parent proxy via the MN’s home network.

4. When the parent PA receives a join packet, it will check if the included (in the payload) RSSI value is acceptable and if the PAN ID is the same. If yes, it will answer to the proxy node with an accept message (Join Ack packet). In the case where more than one surrounding proxies exist, the parent proxy will receive more than one Join packets and will accept the one with the stronger RSSI value. This means that it must be pre-configured to wait for a specific time interval before sending a Join Ack message in order to make sure that all possible Join messages arrive.

5. The new proxy will then inform the edge router that the MN is now served by him (location update). The previous proxy will inform the MN with a Proxy Confirmation message about the new attachment point.

6.4.2 The Inter-PAN Mobility Scenario

In this section, we study the mobility of the MN between PAN networks. Our proposed mobility model is based on the following assumptions:
1. 6LoWPAN proxy agents located in different networks will advertise different prefixes.

2. Home Agents have direct access between them.

3. The address of the MN when moving between different PANs is changed.

4. The parent proxies have all the necessary information to perform the Duplicate Address Detection (DAD) procedure on behalf of the MN.

5. The Home Agents are responsible for creating the 16-bit address of the MN that will be used to route packets inside the 6LoWPAN network.

6. The Home Agents will maintain a binding table where the Global IPv6 address, the Care-of Address, the 16-bit address, the parent proxy address and a timestamp will be stored as shown in Table 18.

<table>
<thead>
<tr>
<th>Global IPv6 Address</th>
<th>Careof Address</th>
<th>Short Address</th>
<th>Proxy Address</th>
<th>Timestamp</th>
</tr>
</thead>
</table>

The inter-PAN mobility procedure is the following:

1. The first 3 steps are the same as in new proxy intra mobility scenario.

2. When the parent PA receives a join packet it will check if the RSSI value is acceptable and if the PAN ID is the same. If the PAN ID is different it will assume that the MN has moved to a new network.
3. In case where more than one surrounding proxies exist, the parent proxy will receive more than one Join packets and will accept the one with the strongest RSSI value. This means that it must be pre-configured to wait for a specific time interval before sending a Join Ack message in order to make sure that all possible Join messages arrive.

4. After the expiration of the predefined interval, the PA will decide which proxy is the best for the MN and it will create and send the fast compressed binding update (FCBU) to the HA. The HA will create a Binding Update message and sent it to the backbone router. After that, the Binding acknowledgement will be sent to the HA by the backbone router and, finally, the fast compressed BA will be sent to the parent proxy. The HA will start buffering the data that are destined to MN until it receives the Location Update message.

5. Finally, the Proxy Confirmation will be sent to the MN from the previous proxy so that to confirm the 16-bit IPv6 address to use. At this time, the MN is routable via its new Home Agent.

6. In order to avoid any security threats we aim to use security keys.

The handoff procedure is initiated by the proxy and is proactive. The basic idea behind this is to leverage information from the link-layer technology to either predict or rapidly respond to a handover event. Through this way, we can reduce the handoff time and, subsequently, any packet losses and delays. Moreover, the
MN should be left out of any mobility signalling. The signalling of the proposed solution is presented in Figure 130.

The PANs mainly use different frequencies in order to avoid interference. For that reason, the proxy agents at the edges of PANs that are configured to serve the MN should be able to capture packets from different frequencies and PANs as well, if any in range. In order to handle the scenario where the MN is moving without communicating, the proxies must be configured to send advertisements to their serving MNs in a predefined interval (every seconds where ) so that to guarantee that the node mobility can be detected. Additionally, the MN will be aware of that interval. If the advertisement is received inside that interval the MN will continue its normal behaviour, as shown in Figure 131 (a). In case that the advertisement interval value is expired without receiving any advertisement, the MN will transmit an alive message to the parent proxy and will wait to receive an acknowledgement. If not acknowledged then the MN wait to receive advertisement packets from another
proxy node as shown in Figure 131 (b). With this solution, we can assure that it is possible to control the maximum disconnection time during handoff and that the MN movement can always been detected.

![Figure 131: MN mode state.](image)

6.4.3 Proposed Message Format

In this section, we define the format of the mobility messages of our proposed solution. The format is recommended based on the RFC 4944 [6] and the relevant IPv6 header compression format for IPv6 packet delivery in 6LoWPAN networks [13]. The compression format relies on shared context to allow compression of arbitrary prefixes. For that purpose, the 6LoWPAN working group defined a new encoding for compressing IPv6 header, called LOWPAN_IPHC. In addition, we used a new encoding format for arbitrary next header, called LOWPAN_NHC. The proposed messages format is shown in Figure 132. Based on the proposed mobility model, the communication can be separated in two categories: intra communication where nodes inside the same PAN exchange messages and inter communication where the communication is between two nodes that belong to different PANs. In the former case the link local unicast addresses are used and the IPv6 header can
be compressed down to 6 bytes. In the latter case the global addresses are used and the header can be compressed down to 10 bytes. Additionally, the compression gain of the IPv6 header is also significant in case of well-known multicast addresses as LOWPAN_IPHC can compress the header down to 7 bytes. The main overhead in the proposed solution is the Frame Header where it is 22 bytes. The Frame Header structure is depicted on Figure 133.

As discussed previously, the packet formats are based on the LOWPAN_IPHC encoding compression. In order to support the 3 different types of communication
(multicast, link-local and global) we define the following cases for the values of LOWPAN_IPHC as shown in Table 19.

Table 19: IPHC header values

<table>
<thead>
<tr>
<th>Dispatch</th>
<th>IPHC</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>011</td>
<td>1111001111011</td>
<td>Multicast</td>
</tr>
<tr>
<td>011</td>
<td>1111000110011</td>
<td>Link-local</td>
</tr>
<tr>
<td>011</td>
<td>1110011100110</td>
<td>Global</td>
</tr>
</tbody>
</table>

The LOWPAN_IPHC utilizes 13 bits and uses the 5 rightmost bits of the dispatch type. In addition to the LOWPAN_IPHC encoding, we defined the mobility header using the LOWPAN_NHC encoding so that to support the mobility signalling of the proposed solution. The proposed mobility header is shown in Table 20.

Table 20: Mobility Header

<table>
<thead>
<tr>
<th>Mobility Header</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000001</td>
<td>FCBU</td>
</tr>
<tr>
<td>00000010</td>
<td>FCBAck</td>
</tr>
<tr>
<td>00000011</td>
<td>Trigger</td>
</tr>
<tr>
<td>00000100</td>
<td>Join</td>
</tr>
<tr>
<td>00000101</td>
<td>Join Ack</td>
</tr>
<tr>
<td>00000110</td>
<td>LU</td>
</tr>
<tr>
<td>00000111</td>
<td>Proxy Conf</td>
</tr>
</tbody>
</table>

6.4.4 Preliminary Evaluation

In this section, we evaluate the handover delay of the proposed mobility model analytically. We consider the inter mobility scenario where the MN moves from the
home network PAN1 to the visited network PAN2. For that purpose, we will use the topology shown in Figure 128. A mobile sensor node is unable to receive IP packets on its new association point until the handover process finishes. The period between the transmission (or reception) of its last packet through the old connection and the first packet through the new connection is the handover latency. The handover latency in mobility protocols, in general, is affected by several components:

1. Link Layer Establishment Delay ($D_{L2}$): The time required by the physical interface to establish a new association.

2. Bootstrapping($D_{BS}$): The time required for the mobile node to run the ND ($D_{ND}$) and DAD ($D_{DAD}$) procedure.

3. BU/Registration Delay ($D_{REG}$): The time elapsed between the sending of the FCBU from the proxy sensor to the HA and the arrival/transmission of the first packet.

4. Processing and queuing delay ($D_{PROC}$): The time required for processing the messages and the delay that the queues may add.

The general handover delay for all the protocols can analytically be computed as:

$$D = D_{L2} + D_{BS} + D_{REG} + D_{PROC}$$

(15)

In the case of our model the $D_{DAD}$ and the $D_{REG}$ delays are not part of the handoff time since they are performed prior to the disruption point; the address test performed during handover to reduce handover latency. The handoff procedure
is started at the time the MN receives the Router Confirmation message and is finished by the arrival of the first data packet routed via the visited 6LoWPAN network. Thus, the handoff delay is equal to $D_{L2} + D_{PROC}$.

In order to evaluate the signalling cost in bytes we firstly calculate the number of bytes of each message which is sent inside the 6LoWPAN networks. Table 21 depicts the values.

Table 21: Mobility Messages length

<table>
<thead>
<tr>
<th>Message</th>
<th>Number of Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCBU</td>
<td>33</td>
</tr>
<tr>
<td>FCBAck</td>
<td>37</td>
</tr>
<tr>
<td>Trigger</td>
<td>36</td>
</tr>
<tr>
<td>Join</td>
<td>28</td>
</tr>
<tr>
<td>Join Ack</td>
<td>34</td>
</tr>
<tr>
<td>LU</td>
<td>32</td>
</tr>
<tr>
<td>Proxy Conf</td>
<td>44</td>
</tr>
</tbody>
</table>

When a MN moves from one network to another the signalling cost in bytes is equal to the total transmit bytes plus the total received bytes. The total transmit bytes are equal to trigger bytes + FCBU bytes + Join Ack bytes = 103 bytes. The total received bytes are equal to

$$\text{Total} = \#joins \times 37\text{bytes} + \text{FCBAckbytes} + \text{ProxyConfbytes} = 109\text{bytes}$$

Thus, if we consider 1 join inter message the total bytes that are required for the proposed solution are equal to 212 bytes. Based on our solution, only the reception of the 44 bytes involves the MN. Figure 134 depicts the case of signalling cost in bytes without the proxy node, thus, all the signalling is handled by the MN and the
case where the proxy exist and takes care of the mobility signalling (as proposed). We observe that the proposed solution managed, as it was aimed, leaves the MN outside of the mobility related signalling.

![Figure 134: MN signalling cost](image)

In addition to the MN signalling cost, we use the same approach as in [22] in order to calculate the overhead of the proposed system regarding the overall signalling cost. To do so, we assume that the probability of the MN staying in the current 6LoWPAN WSN is $p$, and the probability of the MN moving into another 6LoWPAN WSN is $1-p$. Using Markov chain, the one-step transition probability matrix is show in 17:
\[
\begin{bmatrix}
p & 1-p \\
1-p & p \\
\end{bmatrix}
\] (17)

If we assume that \( \pi_0 \) is the long-term steady-state probability of the MN staying in the current PAN and \( \pi_1 \) is the long-term steady-state probability of the MN moving into another PAN we acquire the following Equations 18:

\[
\pi_0 + \pi_1 = 1
\]
\[
\pi_0 = p \cdot \pi_0 + (1-p) \cdot \pi_1
\]
\[
\pi_1 = (1-p) \cdot \pi_0 + p \cdot \pi_1
\] (18)

In order to calculate the signalling cost of the proposed solution, we use the formula 19 that was proved in [22] and modified the method to reflect our protocol in signalling cost.

\[
C_T = \frac{\pi_0 C_{\text{Intra}} + \pi_1 C_{\text{Inter}}}{T}
\] (19)

where the \( C_{\text{Intra}} \) is the signalling cost for the Intra mobility, \( C_{\text{Intra}} \) is the signalling cost for the Inter mobility and \( T \) is the average resident time.

In our case formula 19 can be broken down to the following:

\[
C_{\text{Intra}} = D_{MN,P} \cdot \kappa \cdot P_{\text{Proxy,conf}} + C_{MN}
\] (20)

where \( P_{\text{Proxy,conf}} \) indicates the packet size of the Proxy Confirmation, \( D_{MN,P} \) indicates the hop distance between MN and Proxy and \( C_{MN} \) is the processing costs for routing and binding procedures on the MN.
\[ C_{\text{Inter}} = C_{\text{Triggering}} + C_{\text{Binding}} + C_{LU} \]  

(21)

\[ C_{\text{Inter}} = C_{\text{Triggering}} + C_{\text{Binding}} + C_{LU} \]

\[ C_{\text{Triggering}} = D_{P, NP} \cdot \kappa \cdot P_{\text{Trigger}} + C_{NP} + D_{NP, P} \cdot \kappa \cdot P_{\text{Join}} + C_P \]

\[ C_{\text{BIND}_{P}} = D_{P, HA} \cdot \kappa \cdot P_{\text{FCBU}} + C_{HA} + D_{HA, P} \cdot \kappa \cdot P_{\text{FCBA}} + C_P \]

\[ C_{\text{BIND}_{HA}} = D_{HA, GW} \cdot \tau \cdot P_{BU} + C_{GW} + D_{GW, HA} \cdot \tau \cdot P_{BA} + C_{HA} \]

\[ C_{\text{REG}} = D_{P, NP} \cdot \kappa \cdot P_{\text{JOINACK}} + C_{NP} \]

\[ C_{LU} = D_{NP, NHA} \cdot \kappa \cdot P_{LU} + C_{NHA} \]

where \( D_{x,y} \) indicates the hop distance between two entities, \( P_x \) is the the packet size of the message \( x \) and \( C_x \) is the processing costs for routing and binding procedures on the entity \( x \).

For comparison reasons, we use the following parameter values used in [86][22] \( \tau = 1, \kappa = 2, D_{HA, GW} = 5 \). For simplicity, we consider that processing costs for routing and binding procedures are the same for all nodes and equal to \( C = 30 \).

Figure 135 shows the total signalling costs with various average resident times. We observe that when \( \pi_1 \) is large, the total signalling cost is also increased which means that when the probability of inter-PAN movement is high the overhead is more. The total signalling cost is reduced as the average resident time of MN increases.

Figure 136 compares the proposed solution with the MIPv6 mobility solution and the Inter-Mario [86] mobility solution in terms of the total signalling cost. As
Figure 135: Total signalling cost as a function of average resident time.

We observe, our solution managed to reduce the overall signalling cost compared to the other two solutions.
Figure 136: Comparisson of different total signalling cost for $\pi_1 = 0.5$

6.4.5 Conclusion

Nowadays, critical applications require mobile sensor nodes to be uniquely addressable. To support the movement of those sensor nodes, a new mobility protocol is needed since the existing solutions cannot be applied to such networks. In this chapter, we proposed a mobility model that promises controlled disconnections between different PANs. We also define the format of the mobility messages along with their compressions. The model is based on the involvement of a proxy node that is responsible to handle, on behalf of the MN, the mobility related messages. A network assisted mobility support is actually provided to the MN. This work has
performed a detailed decomposition and analysis of the handover delay and our solution was compared with the MIPv6 and the Inter-Mario solutions. The comparison shows that our model outperforms both solutions in terms of signalling cost and the of MN to the handoff procedure.
Chapter 7

Conclusions

In this thesis, the problem of mobility management in industrial WSNs is addressed. The aim of this study is to support the mobility of nodes in critical application scenarios with performance requirements and to achieve seamless connectivity of the MN by controlling the handoff procedure. The handoff procedure could be divided into two main sub-procedures, the triggering and the handoff decision/execution.

First we gave an introduction to the problem of mobility management in the field of industrial wireless sensor networks. Then, we described the mobility scenario and the system architecture. The first practical step of this work was to propose a radio propagation model based on a refinery setting with final scope the integration of this model to COOJA simulator. In this way, we were able to perform extensive evaluation using a simulation environment that, with high probability, could give results that correspond to the real setting results.
The first approach to solve the mobility management, was to investigate the performance of the single-based metric handoff triggering solutions. The idea behind this step was the fact that in the literature many existing works proposed the use of the RSSI metric as a handoff triggering solution. Since there was not any implementation of such functionality, we proceeded with the implementation of the single-based solutions that include the use of metrics like the RSSI, Link Loss, Burst loss, Simple Moving Average of the RSSI and the Link Loss and the Estimated Weighted Moving Average of RSSI and Link Loss.

The second approach was to use fuzzy logic control principles to design a simple, effective and efficient non-linear control law, in order to provide a system that will manage to control the handoff triggering procedure and provide improved performance. We proposed the FLMC solution which is shown to outperform any other solution and proven to be suitable of use in unpredictable environments like the refinery.

Regarding the handoff decision/execution phase, we used three different options. The first option was the use of the RSSI with hysteresis margin, the second option was our proposed Burst Loss Algorithm (BLA) using multiple attachment point and the third option was a combination of the two aforementioned options.

Finally, we proposed a new network-based mobility model able to provide mobility support in 6LoWPAN networks. This model includes the proposal of the mobility signalling, the packet format and the operation of the MN. Due to the lack
of 6LoWPAN standards, we proceeded with analytical evaluation of our proposal and compared it with other solutions.

In what follows, we first give an overview of the contributions and findings of this thesis, then discuss possible future research directions, and finally give a closing statement.

7.1 Contribution and findings of this thesis

The main scope of this thesis was to provide mobility solutions able to achieve seamless connectivity of the MN by controlling the handoff procedure inside a refinery setting. The refinery environment is unpredictable with high levels of electromagnetic interference and with metal structures and pipes acting as obstacles to radio communication. The use of the specific setting poses unique challenges to the proposal, implementation and evaluation of the mobility management solutions.

The main contribution of this work is the proposal of an intelligent controller, named FLMC. This controller enables sensor mobile nodes to intelligently decide whether they have to trigger the handoff procedure and perform the handoff to a new position or not. The approach taken has greater applicability to any WSN industrial environment or testbed setting with mobility requirements, due to the fact that it was designed based on network state parameters that are available to all sensor mobile nodes. Furthermore, the selection of the Fuzzy Logic was based on the fact that it can process and handle multiple inputs. To prove that the proposed
Fuzzy Logic-based solution performs better compared to any other single-based solution, we performed extensive evaluation using different parameters/settings like the use of different physical and logical topologies and different radio propagation models. Finally, we improved the proposed solution performance by using an adaptive thresholding approach. The adaptive FLMC managed to achieve the highest performance by minimizing the End-to-End packet loss to 2.2% and to increase the on-time triggering to 87%.

The remaining contributions of this thesis are the following:

- Examination of the commonly-used Received Signal Strength Indicator (RSSI) based solution in WSNs in order to investigate the best hysteresis margin and to discover the best window size of the Simple Moving Average (SMA) and Exponential Weighted Moving Average (EWMA) extensions; We found that the best hysteresis margin is equal to -5dBm where the best window is equal to 10 packets;

- Proposal of a new handoff triggering mechanism that is based on local link loss characteristics;

- We give a combination of solutions to support the two main phases of mobility control, the triggering and the handoff;

- The single-based handoff triggering evaluation: Considering all the evaluation metrics, we can not easily select the best option since there is a trade-off between End-to-End packet loss, power consumption and on-time triggering.
We can conclude that in the case of single-based metric approach, if the power consumption is not important (e.g. scenarios where energy harvesting is possible), we can use the Link-Loss based solution, or in a different case we can use the RSSI SMA solution instead.

- The proposal of a new handoff decision algorithm, named Burst Loss Algorithm (BLA). The performance evaluation shows that the single BLA handoff performs better than the hysteresis margin handoff but suffers from ping-pong events. On the other hand, the hysteresis margin managed to reduce the ping-pong events. Thus, the combination of both handoff decisions outperforms any single-based handoff decision.

- The characterization of the radio propagation model that was designed based on the oil refinery setting. The integration of this model to a simulation environment helped us to be able to perform extensive evaluation using a simulation environment.

- The proposal of a new network-based mobility solution for 6LoWPAN able to reduce the involvement of MN in the handoff procedure. In such way, the overhead added to MN is negligible.

- A real industrial setting (oil refinery) is used as the evaluation environment.
7.2 Future Research Direction

Here we point out some future research directions that are relevant for the work presented in this thesis:

- **Node physical and logical placement solutions**: the topology control is one of the most important modules regarding the mobility support. In this thesis, we considered different physical and logical placements of the nodes. Despite that, we did not consider a real-time maintenance of the topology. Therefore, a possible extension could be the real-time partially reconstruction of the topology so that to solve performance issues related to the topology. This kind of work will help to solve also the issue of the limited free available positions for the MN. Using this extension, it could be possible to reconstruct the topology and provide a new attachment point for the MN. All these could be useful to solve the open issues of the uncovered areas and therefore to further minimize the packet losses.

- **Implementation of a Fuzzy Logic-based handoff decision**: In this thesis, we used Fuzzy Logic-based techniques in order to support the triggering phase of the handoff. A possible extension could be the use of Fuzzy Logic to support the second phase of the handoff, the handoff decision. In order to implement such solution, it requires also measurements from the candidate attachment point. Thus, we need to enable the multiple attachment point functionality.
The key to the success implementation of this approach is to minimize the execution overhead as much as possible so that to be able to perform experiments without wondering regarding the on-time operation of the system.

- Implementation of the network-based mobility 6LoWPAN solution and evaluation using testbed setting: the applicability of any mobility solution is crucial to be proven under real setting experiments. Therefore, we aim to extend the work presented regarding the 6LoWPAN mobility with an implementation of the system and evaluation using real setting scenarios. It is important to mention that the lack of RFCs regarding the 6LoWPAN technology will be a parameter that may prolong the implementation of this extension.

7.3 Closing Statement

In critical applications, a real-time monitoring system of mobile must always be available. In order to efficiently monitor or control a mobile entity moving in a WSN area, the mobile entity must be able to handoff between different networks while performing its movement. In this thesis, we considered several mobility solutions that were based on a single metric so that to support the handoff procedure. Based on the evaluation of these single metric solutions, we concluded that we cannot rely on such approaches when the targeted application is critical. Hence, we have shown that the use of a multiple input Fuzzy Logic-based is proven to be an effective method for providing mobility control in such critical applications. The proposed Fuzzy Logic Mobility Controller was evaluated under several configurations with
different network and application parameters and proven to perform in a better way compared to any single metric-based solution.
Bibliography


Appendix A

Publications list

This section provides a list of all publications stemming out of this thesis. Major contributions of this thesis have been published in:

**Book Chapter**


**Journal papers**


Conference and Workshop papers


Technical Documents
