Optimisation and Algorithms in Wireless Networks for Mission Critical Applications

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A thesis submitted in partial fulfilment of the requirements of the University of Greenwich for the Degree of Doctor of Philosophy

March 2015

DECLARATION

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy (PhD) being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

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(Second Supervisor).

But don't be satisfied with stories, how things have gone with others. Unfold your own myth.

Rumi

ACKNOWLEDGEMENTS

My PhD journey has certainly been one with a fare share of ups and downs. There were times when I couldn't be happier and enjoyed every seconds of it and there were times when I went through really rough patches that could push me to the edge of insanity. Nonetheless, now that it comes to its end I can say with confidence it was a journey worth going through and not just because of the technical and theoretical knowledge I gained but more importantly because this journey helped me to learn so much more about myself in a clearer light and shaped me to become who I am now.

There are few people who I can not thank and praise enough for their unreserved and unconditional support. My parents who have always supported me and made me feel loved under all circumstances. My love, Amir, who despite his own challenging work always been my best friend and afforded me his best support. I could have hardly hoped for a better mentor than Professor Predrag Rapajic. I am sincerely thankful to have done my PhD under Professor Rapajic advisory and supervision, and not only because of breadth and depth of his knowledge on all things scientific which he freely and willingly shares, but also because of his continuous and endless support and guidance and his encouragement and dedication on training independent and skilled original researchers. If nothing else, I owe a great share of independence and freedom of thought I developed, in my capacity and over the past few years, to him and his wisdom; our many challenging discussions is one of few reasons making my PhD worthwhile.

I also like to express my gratitude to Dr Yifan Chen, during relatively short time when he was my supervisor, I learned a great deal from him for which I am always truly grateful.

Special thanks to Dr Ruiheng Wu for his support as my second supervisor. My gratitude also goes to Medway School of Engineering, University of Greenwich, for funding my PhD research.

I would also like to thank Dr Steve Woodhead, Director of Research Enterprise, and Dr Raj Bhatti, Head of Postgraduate Studies, for their support and assistance over the years.

Im also very grateful to the supporting staff at Medway School of Engineering for their friendly and skilled assistance.

I must also acknowledge colleagues, friends and fellow PhD students at the University of Greenwich, whose contributions made the years of graduate school enjoyable: Dr Ehsan Hamadani, Grace, Benshuai, Ollie, Mojtaba, Moura, and others who I may have forgotten to name here but certainly affected my journey.

I should also thank Institute for Infocomm Research (I2R), A*STAR Singapore for accepting me as an Intern in their research centre during summer 2010. I would like to express my gratitude to Dr Chau Yuen and Dr Chew Yong Huat at I2R for the useful discussions we had and for their guidance. I greatly benefited from the time I spent at I2R Singapore.

I also like to specially acknowledge Arash, my brother, who I know always has my best interest at heart, and my niece, Arshida, who even though is in very early age of life herself, but her presence filled me with love, energy and fun many times I needed it.

I also like to express a special thanks to my in-laws for their support and kindness during the years.

Thanks to my friends in the UK, Iran, Singapore and all around the world. I can not name you all but surely my life would not be as interesting and joyful if we did not have our many conversations, laughs and tears.

Thank you all!

ABSTRACT

The focus of this dissertation is to present novel algorithms and techniques in wireless network systems aiming at performance optimisation. This thesis provides contribution to knowledge on the following topics: (a) sum rate maximisation of two interfering users in an Orthogonal Frequency Division Multiple Access (OFDMA)-based cooperative base stations and (b) event-region detection in Wireless Sensor Networks (WSNs).

The first area of work makes contribution on problem of maximising the sum rate of two interfering users, while limiting the received interference at each user. An OFDMA-based system operating in downlink is considered. Comparisons between achieved average spectral efficiency of proposed interference power constraint resource allocation scheme as opposed to achieved average spectral efficiency by non-cooperative Time Division Multiple Access (TDMA) method is provided to prove that the proposed cooperative Base Stations (BSs) scheme outperforms non-cooperative TDMA.

The second area of work makes contribution on problem of event region and event boundary detection in WSNs. A new method for classifying randomly deployed sensor nodes over an area of interest into distinctive categories is provided. In this work, a network of spatially distributed and wirelessly connected sensor nodes commissioned to detect two different phenomena, occurring in distant parts of an area of interest, is considered. Analysis on correlation between statistical attributes of received signal distribution at each node and the node's regional position with respect to two events is provided. Simulation results proves that each node can acknowledge its regional position based only on the statistical attributes of its own environmental readings. This is a promising approach because if only the nodes placed in the close-by region of each phenomena report back their reading to the Base Station (BS), as opposed to transmitting entire readings from all nodes, the required bandwidth reduces to be proportional to the size of that event-region only.

ABBREVIATIONS

AWGN	Additive White Gaussian Noise
BS	Base Station
BSs	Base Stations
CDMA	Code Division Multiple Access
CR	Cognitive Radio
CSI	Channel State Information
DCF	Distributed Coordination Function
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
KKT	Karush-kuhn-Tucker
LAN	Local Area Network
LTE	Long Term Evolution
MAC	Media Access Control
MEMS	Micro Electro Mechanical Systems
MSE	Mean Square Error
MU	Multi User
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

PCF	Point Coordination Function
pdf	Probability Density Function
PSD	Power Spectral Density
PU	Primary User
PUs	Primary Users
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
REI	Residual Energy Information
SES	Standard Error of Skewness
SINR	Signal-to-Interference-plus-Noise Ratio
SIR	Signal to Interference Ratio
TDMA	Time Division Multiple Access
UWB	Ultra-wideband
VLSI	Very Large Scale Integration
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLANs	Wireless Local Area Networks
WSN	Wireless Sensor Network
WSNs	Wireless Sensor Networks
3GPP	3rd Generation Partnership Project

SYMBOLS AND NOTATIONS

$h_{i,n}$	Channel power from BS-i to edge user i in sub-channel n
$g_{i,n}$	Interference power from BS-j to edge user i, in sub-channel n
w	Bandwidth
$f(h_{i,n})$	pdf of $h_{i,n}$
$P_{i,n}$	Transmitted Power for user i of BS-i in sub-channel n
$Q_{j,n}$	Transmitted Power for user j of BS-j in sub-channel n
$\sigma^2_{i,n}$	PSD of AWGN for user i of BS-i in sub-channel n
$\sigma^2_{j,n}$	PSD of AWGN for user j of BS-j in sub-channel n
τ_A	Threshold level of interference for user i
τ_B	Threshold level of interference for user j
$L(P_{i,n}, Q_{j,n}, \lambda_A, \lambda_B)$	Lagrangian dual function
λ_A	Lagrangian multiplier
λ_B	Lagrangian multiplier
$E\{h_{i,n}\}$	Average channel power gain for user i, direct links
$E\{h_{j,n}\}$	Average channel power gain for user j, direct links
$E\{g_{i,n}\}$	Average channel power gain for user i, interference links
$E\{g_{j,n}\}$	Average channel power gain for user j, interference links
P_j	Power transmitted by event j
$p_{j,u}$	Received signal power at node u from event j
α	Path-loss
$X_{j,u}$	Rayleigh fading random variable
$f_X(x;\lambda) = \lambda e^{-\lambda x}$	pdf of Rayleigh fading random variable
$p_{total,u}$	Total received power at node u
μ	Mean
σ	Standard deviation
$\mu^{\circ}_{nX_j}$	nth central moment for random variable X_j
λ_1	Rate parameter of X_1
λ_2	Rate parameter of X_2
$SK(exp(\lambda))$	Skewness of exponential distribution
$d_{1,u}$	Distance from event 1 to node u
$d_{2,u}$	Distance from event 2 to node u distance

CONTENTS

FIGURES

TABLES

List oF PhD Candidate's Publications Related to PhD Thesis

[1] **A. Tavakoli-Dehkordi**, A. Shadmand, C. Yuen, Z. Lei, *Optimal Power Allocation for OFDMA-Based Cooperative Base Stations by Limiting Interference*, Communication Systems (ICCS), IEEE International Conference on, Singapore, p403-407, Nov 2012

[2] **A. Tavakoli-Dehkordi**, Y. Chen, P. Rapajic, C. Yuen, Y.H.Chew, *A Statistical-based Algorithm for Event Region Detection in Wireless Sensor Networks*, Computers and Communications (ISCC), IEEE Symposium on, Croatia, p000593, July 2013

To be Submitted:

[3] **A. Tavakoli-Dehkordi**, P. Rapajic, *An Opportunistic Multiple Access approach to lifetime optimisation of Wireless Sensor Networks*, to be submitted in IET Communications

[4] **A. Tavakoli-Dehkordi**, Y. Chen, P. Rapajic, C. Yuen, Y.H.Chew, *Statistical Approach for Boundary Recognition in Wireless Sensor Networks*, to be submitted in IET Wireless Sensor Systems

Chapter 1

Introduction

The past decade has witnessed an enormous growth of the use of wireless networks, moved by the rapid advancement of portable computing, communication and embedded devices. In addition to this trend, other revolutionary advancements in the wireless communication technologies have enabled the realisation of a wide range of heterogenous wireless systems such as cellular networks, wireless local area networks, wireless sensor networks, etc. The substantial impact of wireless communication systems on modern society along with their significant advancements and rapid growth is opening up various technical and scientific challenges further inspiring the researchers to contemplate many new scenarios such as wireless regional area networks, disaster area wireless networks, vehicular ad hoc networks, next generation digital home networks, cognitive and cooperative networking, etc. However, as wireless networks continue impacting and enhancing our lives, it is severely constrained by limited resources, in terms of time, bandwidth, and power. Smart allocation of network resources, based on the specific network applications, can have extreme effect on the performance enhancement of wireless network systems. In fact, resource allocation for wireless networks is the process of determining how a set of network resources are exploited and based on different network scenarios, smart resource allocation leads to optimisation of different performance objectives. This thesis makes contributions on optimisation algorithms and methods around specific network scenarios. Chapter 2 of this thesis discusses the current literature already carried out by other researchers in the field.

Chapter 3 of this thesis provides an analysis on the problem of maximising the sum rate of two interfering users, while limiting the received interference at each user, in an OFDMA-based system operating in downlink. The result of this work shows that in a cooperative two cell scenario, for each particular user (located in the edge of the cooperative cell and within the area common with the neighbouring cell), it is possible to incorporate the dominant interference effects of the neighbouring cells within the received noise level. In this chapter, a scenario where two cooperative cellular systems operate in the same band is investigated. Firstly, a scenario where each users having only two sub-channels, to communicate, is considered. Then, this approach is extended to a N sub-channel scenario. The results show that proposed cooperative BSs scheme outperforms non-cooperative TDMA case and it can achieve enhanced levels of efficiency by allocating resources more intelligently.

In the Chapter 4 of this thesis, an algorithm is developed for classifying randomly deployed sensor nodes over an area of interest into distinctive categories. In this work a network of spatially distributed and wirelessly connected sensor nodes, monitoring an area of interest is investigated, this network is commissioned to detect two different phenomena occurring in distant parts of the area. Analysis on correlation between statistical attributes of received signal distribution at each node and the node's regional position with respect to two events is provided. In general, the required bandwidth to transmit entire readings from all nodes to the BS for further processing is proportional to the size of the entire network. However, if only the nodes placed in the close-by region of each phenomenon report back their readings to the base station, the required bandwidth reduces to be proportional to the size of that event-region only. With bandwidth being a major resource constraint in WSN systems, as it is in any other wireless communication systems, the latter is a more promising approach for smart use of the network resources.

The introduction chapter provides a background overview on the mentioned topics and also points out the structure of this thesis.

1.1 Resource Allocation in OFDMA System

The growing demand for wireless network services and the desire to maintain connectivity constantly and on the move, along with various constraints in radio resources offer significant challenges to provisioning Quality of Service (QoS). Therefore, allocating and utilising resources efficiently and effectively is critical in design of wireless network system [5]. A dominant method to efficiently allocate and manage channel resources is to share them. The more shared they are the better it is, as long as connection quality is not diminished. Among various techniques for increasing data rate, resource allocation approaches not only provide higher data rates but also enable the system to guarantee the QoS requirements of various services. However, the major cost of sharing radio channels is the unwanted (co-channel) interference generated during the sharing process. Different sharing (multiple access) techniques have different impacts. Beside the (co-channel) interference, wireless networks suffer also from cross-channel interference resulting from imperfect technology, doppler shift and multi-paths propagation [6]. To overcome this challenge, inter-cell interference is mitigated by separating co-channel cells, in the case of narrowband systems, or by spectral spreading in the case of Code Division Multiple Access (CDMA). If the BSs collaborate in detecting the signals they receive, the inter-cell interference represents additional detection dimensionality. This motivates the advent of cooperating base stations which makes use of spectrum flexibly, efficiently and reliably [7, 8]. Chapter 3 of this thesis provides a thorough analysis for an optimal power allocation scheme in OFDMA-Based system with cooperative BSs by limiting interference, and discusses the performance enhancement implemented through this scheme.

1.1.1 Resource Allocation

The recent years has witnessed a progressive advancement in resource allocation techniques. On the other hand, resource allocation is an extensive issue covering a broad range of research challenges creating the need for developing and implementing various optimisation tools and algorithms. Furthermore, different wireless networks aim at distinct service goals and have various design specifications. One network can be seriously constrained by power whereas the other can be severely limited by bandwidth or be critically sensitive to interference level. As such, different networks encounter different resource allocation problems and different characteristics of problems employ different optimisation techniques [9]. The multiple-access scheme is a generic strategy for allocating limited resources, i.e. bandwidth and time, to guarantee the basic QoS, enhance the system performances, and lower the cost for the network infrastructure. Some of multiple-access methods include frequency-division, time-division and code-division multiple access [10]. Fig. 1.1 represents an overview of the three most-common multiple access techniques, namely: TDMA, Frequency Division Multiple Access (FDMA), and CDMA. In (a) TDMA the system dimensions are divided along the time axis into non-overlapping channels, and each user is assigned a different cyclically-repeating time-slot, these TDMA channels occupy the entire system bandwidth. In (b) FDMA the system signalling dimensions are divided along the frequency axis into non-overlapping channels, and each user is assigned a different frequency channel. In (c) CDMA the information signals of different users are modulated by orthogonal or non-orthogonal spreading codes, the resulting spread signals simultaneously occupy the same time and bandwidth [11].

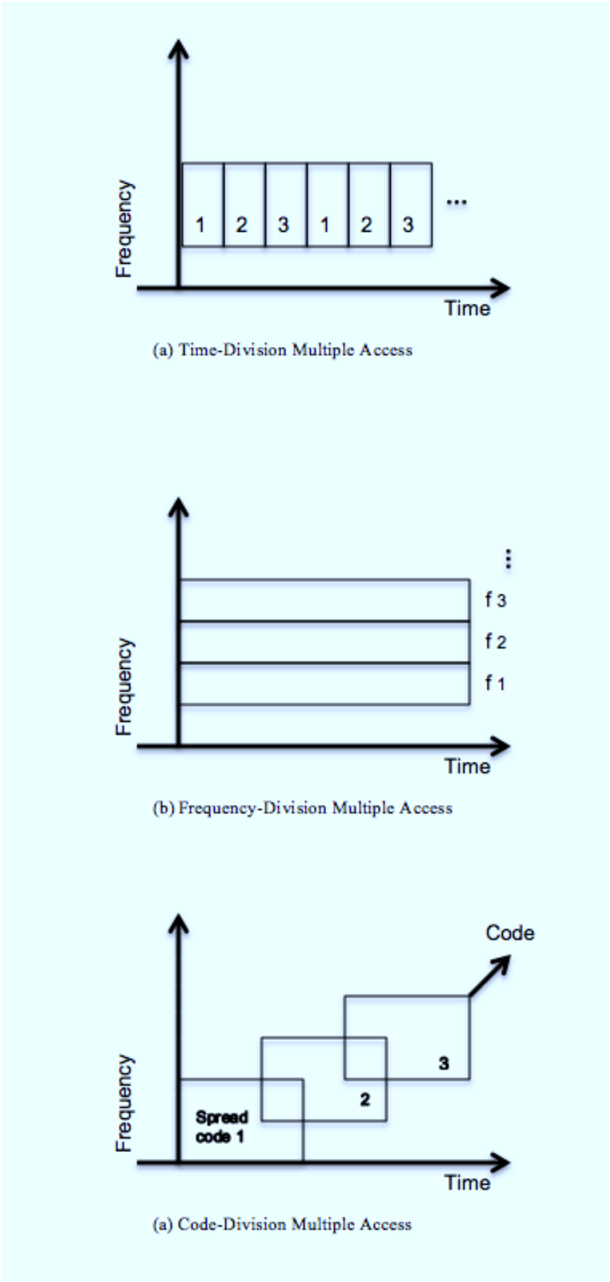

Figure 1.1: Overview of Most-Common Multiple Access Techniques:
(a) TDMA, (b) FDMA, and (c) CDMA

1.1.2 OFDMA System

Multiple access in Orthogonal Frequency Division Multiplexing (OFDM) systems, called OFDMA, implements FDMA by assigning different subcarriers to different users. The principle of OFDMA is based on the use of narrow, mutually orthogonal sub-carriers. Different sub-carriers maintain orthogonality as at the sampling instant of a single sub-carrier, the other sub-carriers have a zero value. The actual transmission is then done by transmitting a signal after the Fast Fourier Transform (FFT) block, which is used to change between the time and frequency domain representation of the signal [12]. From the receiver perspective, this kind of signal is ideal as it does not need equaliser but only needs to compensate the channel amplitude and phase impact on the different sub-carriers. In the receiver side, the FFT is again used to convert back from the frequency domain single signal to the time domain representation of multiple sub-carriers as shown in Fig. 1.2 [1].

Mathematically, modulating a waveform and adding it is equivalent to taking an Inverse Fast Fourier Transform (IFFT). This is because the time domain representation of OFDM is made up of different orthogonal sinusoidal signals which are nothing but inverse Fourier transform. Hence, the fundamental function of an FFT block is to represent the frequency components from which the time-domain signal is constructed. In the case of OFDMA, the parallel inputs to an FFT can be considered as the frequency-domain components which are then converted to

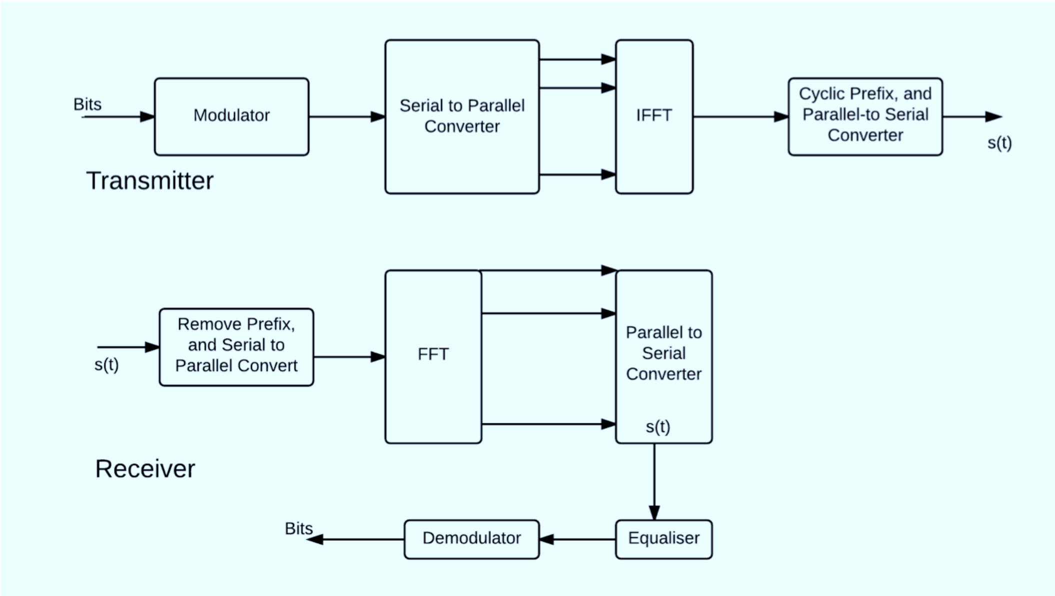

Figure 1.2: OFDM Transmitter and Receiver Diagrams [1].

a single time-domain signal, thus carries in a single long symbol typically up to 512, 1024, or 2048 modulated symbols.

Furthermore, parallel sub-carriers in the receiver with their own modulation and modulation order convert the signal back to parallel Quadrature Amplitude Modulation (QAM) symbols. The simplest type of digital modulation involves transmitting a sequence of waveforms "symbols" $s_i(t)$ of equal duration T where each waveform is chosen independently from a set of M. This allows to transmit up to $b = log_2(M)$ bits per symbol. A common sets of such symbols are those where the real and imaginary parts of the complex baseband signal are each modulated in amplitude. This known as QAM [13].

On the other hand, frequency-selective fading gives rise to Inter Symbol Interference (ISI) where the received symbol, over a given symbol period, experiences interference from other symbols that have been delayed by multi path [14]. Therefore, from a practical point of view, the transmitter needs a cyclic prefix to combat ISI, in fact the ISI can be completely eliminated through the use of a cyclic prefix.

The guard interval could be considered as a kind of break in the transmission, but the waveform is actually continuous. The transmitter takes part of the waveform to be transmitted and copies part of that to the beginning of the symbol to be transmitted. This part just needs to exceed the channel impulse response duration, in order to achieve no inter-symbol interference. The receiver ignores the particular cyclic prefix added. The receiver sees only a single symbol, —as the channel impulse response is much smaller than the symbol duration— making the channel influence like a finite impulse response filter.

The important element of OFDMA is that the transmission can be located in different places in the frequency domain; whereas with Wideband Code Division Multiple Access (WCDMA), by definition, the transmission bandwidth was always independent of the information bandwidth. This allows for use of the frequency-domain element in the scheduling.

1.2 Network of Wireless Sensor Nodes

The capability of WSN systems makes them a technologically-advance solution for many mission critical applications. As a main part of this thesis contributes to specific challenges and research questions in WSN, the aim of this section is to provide an essential overview on concept, structure and challenges of these systems while also presenting some of its well-known applications.

The remarkable progress in technologies like Micro Electro Mechanical Systems (MEMS), Very Large Scale Integration (VLSI) and wireless communications contribute to design and development of low-cost, low-power, small-size, multifunctional sensor nodes capable of communicating wirelessly [15]. Sensor nodes link the physical with the digital world by capturing and revealing real-world phenomena and converting these data into a form that can be processed, stored, and acted upon. When many sensor nodes cooperatively monitor large physical environments and wirelessly communicate with each other and with BS, to disseminate their collected data to remote processing, visualisation, analysis, and storage systems, they form a WSN. On another note, many applications such as disaster relief operations require hundreds or thousands of sensor nodes, often densely deployed in remote area and inaccessible terrains, either inside the phenomenon or very close to it. The position of sensor nodes need not be engineered or predetermined, this allows random deployment in inaccessible areas. To cover these applications, apart from a sensing component, a wireless sensor also includes of on-board processing unit, a communication component, and storage capabilities. Featuring these enhancements, along with data collection a sensor node often performs in-network analysis, correlation, and fusion of locally collected data [2]. Fig. 1.3 visualises the components forming a basic wireless sensor node .

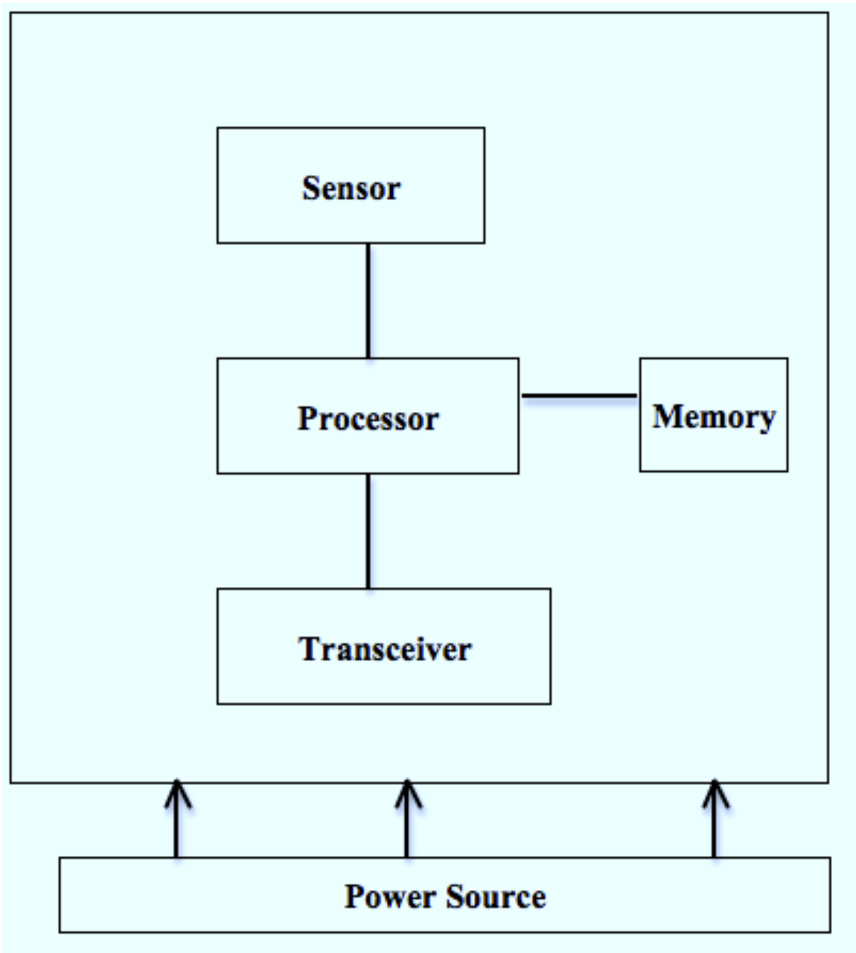

Figure 1.3: Block Diagram of a Basic Wireless Sensor Node

Based on network scenarios and the target application, various types of sensor nodes can be employed in designing a WSN system. While simple sensor can monitor single phenomenon and may only collect and communicate information about the observed environment, more complex and powerful devices (with large processing, energy, and storage capacities) are capable of combining various sensing techniques (acoustic, optical, magnetic) and performing extensive processing and aggregation function. A typical WSN monitoring an area of interest, sensor field, in which sensor nodes communicating both with each other and with a BS to transmit data to the Internet and Satellite - for further processing, analysis, and storage - is shown in Fig. 1.4.

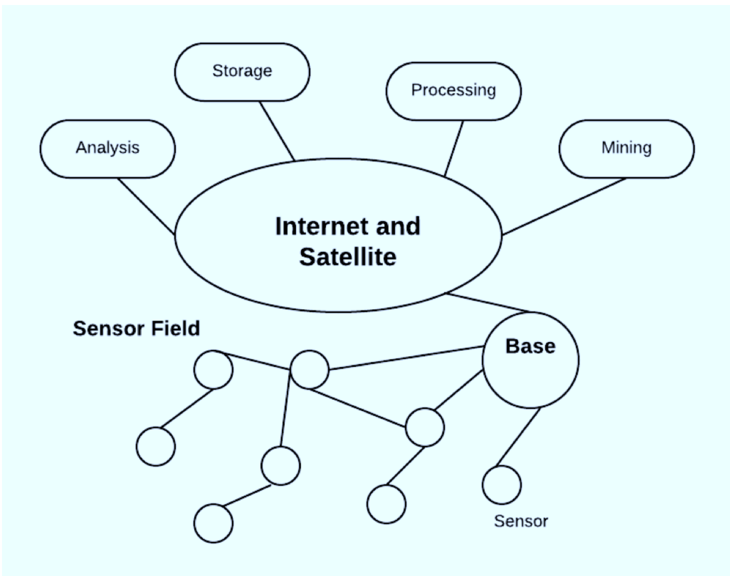

Figure 1.4: Wireless Sensor Network Model [2].

1.2.1 WSN Challenges

In this section we review technical challenges and research questions in the field of WSN for the purpose of this thesis. With an emerging need in environmental monitoring, as a main application of WSN, research on event detection or classification in WSNs gained considerable amount of work recently. Also, as introduced in section 1.2, an attractive feature of WSN is making local observations of the covered area and producing a result reflecting the status of the environment in a collaborative manner. This collaboration requires local processing of the collected data at each node, communication between different nodes and BS. The main concept of collaborative signal processing is that the information from each individual node can be fused to obtain an improved final decision. There are two kinds of event detection problems in WSN. One is when all the sensors collaborate to detect or classify a common underlying phenomenon. Decentralised detection techniques are employed to make a final decision at the BS. In the other detection problem, sensor nodes may observe different local phenomena and they are asked to determine where the regions or boundaries of different local phenomena are located by analysing distinguishable collected attributions of the monitored area [4]. As it can be seen in the Chapter 3 of this thesis, there are scenarios in which sensor nodes are responsible for processing data locally. Instead of immediately sending the raw data to the nodes responsible for the fusion or the BS, they use their onboard processing abilities to carry out computations and transmit only the required and partially processed data. Sensor networks are subject to communication and computation constraints. The reasons behind these constraints are size and cost limitations: many of the most interesting applications require tiny and cheap sensors creating an trade-off between energy (and device size) spent on communication versus computation, and it is not always clear which of the two is the true bottleneck. Some experts show that in current circuitry, the amount of energy spent on computation at least equals if not exceeds the transmit energy. Other experts use "Moore's law" to argue that any computational bottleneck will disappear and that we are still very far away from the ultimate limits of quantum computation [16]. Nevertheless, as sensor nodes rely on battery-powered sources, energy consumption and lifetime is always of main concern in design of WSN. Therefore, lifetime maximisation is a critical concept and there is a growing body of literature on this subject [17], [18].

1.2.2 WSN Applications

To allocate resources smartly in WSNs it is of great importance to understand and analyse based on the specific network scenarios and applications. The emergence of the WSN paradigm has triggered extensive research on many aspects of it. However, the applicability of sensor networks has long been discussed with emphasis on potential applications that can be realised using WSNs. In this section, we present few of promising commercial and academic applications developed for WSNs.

These systems can help to avoid catastrophic infrastructure failures, conserve precious natural resources, increase productivity, enhance security, and enable new applications such as context-aware systems, smart home and health technologies, e.g. sensor nodes can also be deployed to monitor patients and assist disabled patients. While defence and aerospace systems still dominate the market, there is an increasing focus on systems to monitor and protect civil infrastructure (such as bridges and tunnels), the national power grid, and pipeline infrastructure. Networks of hundreds of sensor nodes are already being used to monitor large geographic areas for modelling and forecasting environmental pollution and flooding, collecting structural health information on bridges using vibration sensors, and controlling usage of water, fertilisers, and pesticides to improve crop health and quantity. Fig.1.5 illustrates a generic view of main categories of applications in WSNs.

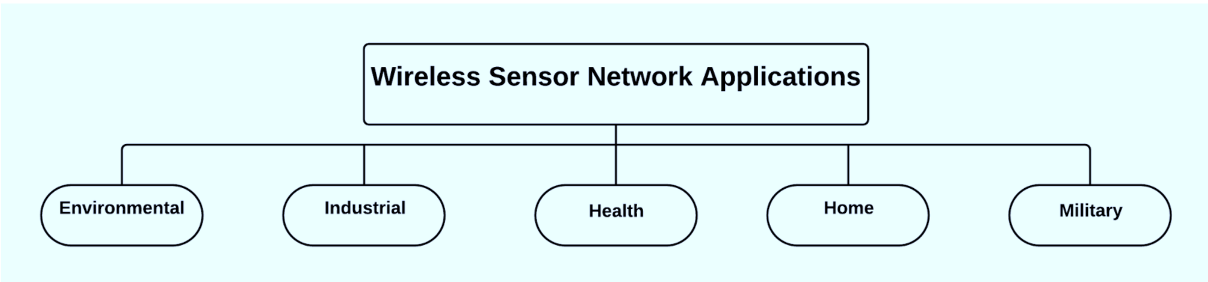

Figure 1.5: Main Categories of Wireless Sensor Network Applications

1.3 Main Contributions

The main contributions presented in this thesis are:

- Maximising the sum rate of two interfering users, while limiting the received interference at each user. An OFDMA-based system operating in downlink is considered. It is shown that the interference power constraint resource allocation scheme can achieve excellent levels of efficiency by allocating resources more intelligently. Results prove that proposed cooperative BSs scheme outperforms compared with non-cooperative TDMA case.
- Event region and event boundary detection in WSN. A new method for classifying randomly deployed sensor nodes over an area of interest into distinctive categories is provided. In this work, a network of spatially distributed and wirelessly connected sensor nodes commissioned to detect two different phenomena occurring in distant parts of an area of interest is considered. Analysis on correlation between statistical attributes of received signal distribution at each node and the nodes regional position with respect to two events is provided.

1.4 Thesis Structure

The introduction chapter provides the basic overview and chapter 2 discusses the current literature already conducted by other researchers, in the field of wireless communication and WSNs systems.

Chapter 3 provides an analysis on the problem of maximising the sum rate of two interfering users, while limiting the received interference at each user. In this work, an OFDMA-based system with cooperating BSs operating in downlink is investigated.

Chapter 4 provides a statistical approach for event region detection in WSNs.

Chapter 5 provides a review of the overall contributions of this thesis and also paves the way for future work on the proposed algorithms and solutions presented in chapter 3 and chapter 4.

Chapter 2

Literature Review

2.1 Related Work

This chapter presents the existing related literature around the topics and challenges covered in this thesis. It is organised as follows: Firstly, the existing schemes and methods of resource allocation in OFDMA and cooperative based wireless systems is discussed. Secondly, the existing studies for event region detection in WSN is presented.

2.1.1 Resource Allocation in OFDMA-based system

With the breakthrough development of digital signal processing high data rate, many of the technical challenges correlated with the adverse and changing propagation conditions in mobile radio communication have been answered. Multi-megabit data rates to portable mobile terminals are no longer science fiction, but reality. As the engineer seems to have the upper hand in this struggle against nature, nowadays very much of the development and improvement efforts are focused on the struggle for limited resources, such as the frequency spectrum and power. The question is not anymore only if wide-band wireless communication can be provided everywhere, but rather, if it is affordable. In [19], the authors address the problems of radio resource management for wireless networks focusing on various angles including: multi-user communication theory, static resource management and cellular system design, various elements of resource management such as handoffs, dynamic channel allocation, and transmitter power control. It also discusses FDMA/TDMA type (orthogonal) waveforms and resource management issues in CDMA system.

In wireless communication systems, mobile users adapt to a time varying radio channel by regulating transmitter powers. This power control is intended to provide each user an acceptable connection by eliminating unnecessary interference. The author in [20] made an attempt to unify and extend convergence results for cellular radio systems employing iterative power control methods. Based on their results and for a variety of systems, interference constraints derived from the users' Signal to Interference Ratio (SIR) requirements, share certain simple properties. These properties imply that an iterative power control algorithm converges not only synchronously but also totally asynchronously when users perform power adjustments with outdated or incorrect interference measurements. Even though this work shows that increasing diversity increases the space of feasible power vectors, it remains unclear whether these capacity improvements are significant in actual systems in which the interactions between user mobility, channel fading and power control must be considered. Furthermore, for wireless cellular communication systems, one seeks a simple effective means of power control of signals associated with randomly dispersed users that are reusing a single channel in different cells. By effecting the lowest interference environment, in meeting a required minimum SIR ratio per user, channel reuse is maximised. Authors in [21] present their work on a simple distributed autonomous power control algorithm and its convergence, their introduced closed-loop power control framework is proved to converge to a unique optimal point.

Adaptive modulation techniques have the potential to considerably increase the spectrum efficiency and to provide different levels of service to users, both of which are considered essential for third-generation cellular systems. Authors in [22] propose a general framework to quantify the potential gains of such techniques and study the throughput performance gain that may be achieved by combining adaptive modulation and power control. They show that using adaptive modulation even without any power control provides a significant throughput advantage over using Signal-to-Interference-plus-Noise Ratio (SINR) balancing power control, and also combining adaptive modulation and a suitable power control scheme leads to a significantly higher throughput as compared to no power control or using SINR-balancing power control.

In fact, in multi access wireless communication systems, power control and adaptive modulation are two important mechanism to increase spectral efficiencies, combat time-varying fading channels, and to reduce co-channel interferences. The overall uplink transmitted power is minimised under the constraints that there is no reduction in overall network throughput and each user achieves the desired time-average throughput. Authors in [23], propose an algorithm for enhancing the system efficiency considering time, space, and multiuser diversity. Their proposed scheme reduces the overall transmitted power up to 7 dB and increases average spectral efficiency up to 1.2 bit/s/Hz, compared with the previous known power control schemes. However, the power stops decreasing and spectral efficiency increasing speed is reduced, as the throughput window size is growing. This is because of the time-average throughput constraint for each user. Cooperative transmissions have been proved to be capable of highly improving system performance by exploring the broadcasting nature of wireless channels and cooperation among users. Some work exists on leveraging cooperation for resource allocation among users such that the network performance can be improved. In [3], the authors intend to answer these two cooperation-relative questions: (1) who should help whom among the distributively located users, and (2) how many resources the users should use for cooperation to improve the performance. To answer these questions, they formulate a power optimisation, subcarrier-allocation, and relay-selection problem over a multiuser OFDM network, which is applicable to systems such as Wireless Local Area Networks (WLANs). In the multiuser OFDM network, cooperation among different users is conducted by assigning the subcarriers of the helping users to relay a certain part of the helped users' data, while maintaining the desired rates of both the helping users and the helped users by means of power control and rate adaption. This way, the bandwidth efficiency of the multiuser OFDM system with cooperation is the same as that of the non-cooperative OFDM system. Fig. 2.1 shows the OFDM cooperative transmission network system model used in [3] where user i relays user j's data to the BS. The formulated optimisation problem is an assignment problem for subcarrier usage and corresponding bit loading as well as power control. The result of their proposed scheme shows an overall power saving of up to 50% for the two-user system and 19% to 54% percent for the multiuser case with random locations, compared with the current multiuser OFDM system without cooperative diversity.

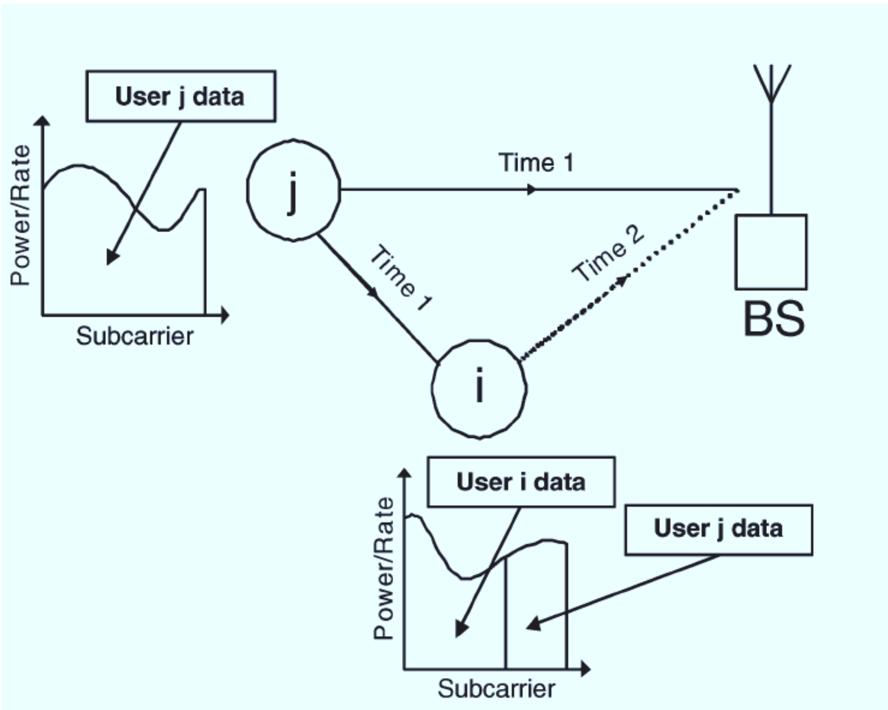

Figure 2.1: OFDM Cooperative Transmission Network [3].

Multiuser OFDM is a promising technique for achieving high downlink capacities in future cellular and wireless Local Area Network (LAN) systems. OFDMA provides a fine granularity for resource allocation, possibly making use of frequency, time and multiuser diversity. In [24], authors proposed a distributed method for resource allocation in multi-cell OFDMA that considers both inter-cell interference and target data rate requirements. It describes a heuristic for distributed sum power minimisation under target data rate requirements. Their proposed method establishes a set of target SINR per user and subcarrier, determined to reach the target data rate of each user, while avoiding power divergence situations. They propose to use a distributed criterion over each subcarrier to ensure that distributed power control will necessarily converge. Compared to iterative water-filling, this method proves to be very efficient at any load in terms of resource consumption and users' rejection. Authors in [25] study the resource allocation problem for the relay-assisted OFDMA-based multiuser system and proposed a new transmission protocol, named hierarchical OFDMA to support two-way communications between the BS and each Multi User (MU) with or without an assisting relay station in "relay" or "direct" mode, respectively. Their results show that substantial system throughput gains are achievable by the proposed two-way relaying and optimal resource allocation schemes over the traditional one-way relaying and fixed resource allocation schemes for relay-assisted OFDMA-based wireless networks. The ability of OFDMA to cope with both ISI and inter-user interference, combined with its low complexity of implementation, have made it a popular choice for the next generation wireless networks. The authors in [26] obtain the optimal power allocation policies, for a two user cooperative OFDMA system with full Channel State Information (CSI), which maximise the rate region achievable by a channel adaptive implementation of inter-subchannel block Markov superposition encoding, used in conjunction with backwards decoding. Their result show that the gain from power allocation is still significant even when the CSI feedback is limited. The authors in [27] develop a transmit power adaptation method that maximises the total data rate of multiuser OFDM systems in a downlink transmission. They formulate the data rate maximisation problem by allowing that a subcarrier could be shared by multiple users. The transmit power adaptation scheme is derived by solving the maximisation problem via two steps: subcarrier assignment for users and power allocation for subcarriers. Their result shows that the data rate of a multiuser OFDM system is maximised when each subcarrier is assigned to only one user with the best channel gain for that subcarrier and the transmit power is distributed over the subcarriers by the water-filling policy.

Compared to TDMA and CDMA technologies, OFDMA divides the wireless resource into non-overlapping frequency-time chunks and offers more flexibility for resource allocation. It has many advantages such as robustness against ISI and multi-path fading as well as and lower complexity of receiver equalisation [28]. Owing to these OFDMA has been adopted the core technology for most recent broadband wireless data systems, such as IEEE 802.16 (WiMAX), IEEE 802.11a/g (WLANs), and LTE for 3GPP.

2.1.2 Event-Based Networking and Region Detection in WSNs

Contrary to conventional communication and data networks, sensor networks are made of users (sensor nodes) that are deployed to achieve a common goal, i.e. to sense a common event or to measure highly correlated data due to the spatial correlation of most physical phenomenon. The sensors are cooperative in nature and should work together to fulfil their application requirements. In fact, two properties of sensor networks that can be exploited to improve communication efficiency are: the cooperative nature of the sensors and application-dependent performance measures [16]. The application-oriented nature of the WSNs should be utilised in order to increase the network performance. As an example, for monitoring applications where the traffic follows a periodic pattern, a reservation-based approach can be used to exploit the periodicity in the traffic. A WSN may contain tens to thousands of wireless sensor nodes to monitor the area and they are used in many applications such as security, surveillance, climatic-change studies, and structural health monitoring. In some poor detecting environment, abnormal events often happen in uncertain time, so the sensor nodes are needed to set an alarm precisely and punctually if abnormal events happen. Due to the limited computational power, memory, and communication range of sensor nodes, designing an ideal event detection algorithm needs to be energy efficient, fault tolerant and robust, resource friendly, and adaptive to multiple event types and environment and it must be accuracy and produces less false alarm [29]. From the application's perspective, the data collection process in a sensor network takes place in various approaches. In time-driven schemes (e.g. environmental monitoring) it can be prompted by the internal clock of sensors nodes where they collect and propagate their collected sensor data periodically at pre-determined time intervals. In event-driven schemes (e.g. wildfire detection) or demand-driven networks, nodes only report their collected information when events of interest occur or when triggered by a request from access points. Event-driven localisation is introduced in [2] as a category of localisation schemes based on events that can be utilised to determine distances, angles, and positions. Such events can be the arrival of radio waves, beams of light, or acoustic signals at a sensor node. On the other hand, in event-based applications, where bursty traffic is generated only during events, an access mechanism that is adaptive to the generated traffic is necessary [15]. Event boundary detection is a useful application in WSNs and the challenges of boundary-detection and region-detection has been studied in recent literature. Typically, event boundary detection includes the detection of a large-scale spatial phenomenon such as the transportation front line of a contamination or the diagnosis of network health.

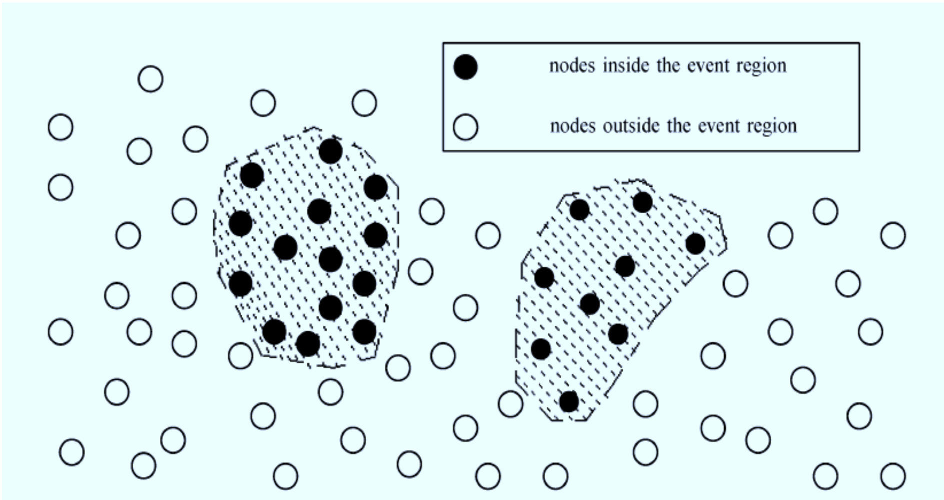

Figure 2.2: Illustration of Event Region Detection in WSN [4].

The authors in [4] explore the problem of event-region detection and the related problem of boundary-region detection in WSNs. Fig. 2.2 shows the event-region detection model used in their work where sensor networks are asked to determine where the regions or boundaries of different local phenomena are located by analysing distinguishable collected attributions of the monitored area. They develop decentralised detection techniques to tackle these problems and a space-memory fusion rule that considers both space-memory information and local detection performance is derived for event-region detection. They compare their strategy with two sequential detection schemes proving that the proposed approach achieves a better performance due to the use of the local detection performance in the fusion process. The authors in [30] present a fully distributed and light-weight secure event boundary detection scheme, which implements secure and fault-tolerant detection of event boundaries in an adversarial environment. An efficient key establishment protocol is first proposed which establishes location based keys at each sensor node to secure the communications. The idea of location-based keys also effectively minimises the impact of node compromise such that a compromised node cannot impersonate other nodes at locations other than where it is. Then a collaborative endorsement scheme is designed to allow multiple nodes collectively endorsing a valid boundary claim for increased resilience against node compromise. Their scheme further develops an enhanced (non-parametric) statistical model that supports localised detection and shows a much better accuracy and fault tolerance property as compared to previous models such as the proposed solution in [31]. The authors in [32] provide a distributed protocol allowing individual sensor nodes to identify themselves as being located on the coverage boundary, which is required in a number of functionalities at both the network and application levels. They develop a deterministic, distributed, localised algorithms for detecting coverage boundary nodes in WSNs. They claim that as a deterministic approach, their algorithm can be applied to any arbitrarily deployed sensor network, do not need knowledge about the distribution of sensor nodes, and only depend on one-hop information, which guarantees the scalability and energy efficiency of the detection algorithms. Due to the nature of WSNs, it is desirable to have a distributed algorithm that has a low computational complexity and a low data communication cost among sensors. The authors in [33] propose a statistical approach to distributed edge sensor detection with WSNs. Their objective is to determine whether a target sensor is located in the edge area of a certain phenomenon or not based on data from its neighbouring sensors. Their result show that it is advantageous to have a radio range larger than the tolerance range (i.e. the distance between the real edge and the edge sensor). However, as the radio range is restricted by the low power consumption requirement of sensors, the value of the radio range and the tolerance range should be assigned adaptively according to the sensor density and the power consumption requirement for each target sensor. The authors in [34] presents a general purpose event detection and tracking algorithm, named DRAGON, claiming to operate in the presence of event splits and merges, finding the right number of events and outlines the right event shapes regardless of deployment type, and regardless of event size, speed, or count. The authors in [] explore the basic trade-off between Mean Square Error (MSE) and energy consumption, as functions of node density. They proposed a method for boundary estimation in sensor networks via complexity regularisation of a hierarchical tree-based estimation method. Their theoretical demonstration show that this method nearly achieves the optimal the optimal MSE/Energy trade-off.

In many cases the main task of WSNs is to monitor, detect, and report the occurrence of events. However, in some applications the detection of event boundary may become more efficacious than detection of the entire event region, e.g. in forest fire and chemical spills scenarios when events span over some geographic region.

Chapter 3

Optimal Power Allocation for OFDMA-Based Cooperative Base Stations by Limiting Interference

3.1 Overview of Optimal Power Allocation in Cooperative Base Stations

In this chapter, the problem of maximising the sum rate of two interfering users, while limiting the received interference at each user, in an OFDMA-based system operating in downlink is considered. In a cooperative two cell scenario, for each particular user (located in the edge of the cooperative cells and within the common area of the neighbouring cells), it is possible to incorporate the dominant interference effects of the neighbouring cells within the received noise level. As applied to the scheme, a scenario where two cooperative cellular systems operate in the same band is investigated. Firstly, a scenario where each user having only two sub-channels, to communicate, is considered. Then, this approach is extended to a N sub-channel scenario. Numerical results show that proposed cooperative BSs scheme outperforms non-cooperative TDMA case and it can achieve excellent levels of efficiency by allocating resources more intelligently.

The growing demand for wireless services has led to deployment of various techniques to increase the data rate. Among these techniques resource allocation approaches not only provide higher data rates, but also enable the system to guarantee the QoS requirements of various services. Along with efficiency and reliability, bandwidth is an important concern as the wireless applications become more and more sophisticated and widely used. Therefore, how to accommodate more wireless services and applications within the limited radio spectrum becomes a big challenge faced by modern society. Furthermore, inter-cell interference is mitigated by separating co-channel cells, in the case of narrowband systems, or by spectral spreading, in the case of CDMA. If BSs collaborate in detecting the signals they receive, the inter-cell interference represents additional detection dimensionality. This motivates the advent of cooperating base stations, which makes use of spectrum flexibly, efficiently, and reliably [7, 8]. With such cooperating base stations, the entire infrastructure can be employed in a system wide detection of each and all mobile user's signals, resulting in major capacity increases, largely through the achievement of full frequency reuse. Different scheduling strategies based on different resource allocation goals demonstrated in defining the corresponding optimisation problems such as sum power minimisation [24,35], sum rate maximisation [36–38], or a combination of these two [39]. In [40], the authors look for distributed, self-enforcing strategies for coexistence in unlicensed bands. They apply non-cooperative Game Theory methods to find fair and efficient solutions. Similar power allocation strategies, but without fairness, and with min-max fairness consideration, for unlicensed band have also been studied in [41]. In this chapter, the problem of maximising the sum rate of two interfering users in multi-cell cooperating BSs OFDMA-based systems operating in downlink is investigated. In a multi-cell cooperative BSs scenario, for each particular user (located in the edge of cell and within area common with neighbouring cell), it is possible to incorporate the dominant interference effects of the neighbouring cells within the received noise level. This chapter mainly focuses on this point. In the aforementioned system, two OFDMA-based cellular systems with two BSs covering different areas is considered. These two cells have a common area in between, where this work is focused only on the downlink of two edge interfering users located within common area of two cells. Authors in [38] proposed sum rate maximisation for two edge interfering wireless users (each user has only one sub-carrier) under the assumption that the power allocation itself is time invariant and frequency flat with maximum power constraints on the links. They considered only power allocation without frequency allocation. In this chapter however, two-dimensions resource allocation is considered. With or without fairness however, most dynamic resource allocation methods still focus purely on the channel conditions of each user, and ignore (partially or fully) the interference effects of edge users on each other. Therefore, this work proposes to use the received interference on K, $K = 2$, edge users as a received interference level, where the goal is to allocate resources, power and sub-channels, in an aforementioned system in a way that no user incurs more than a threshold level of acceptable interference. As applied to the scheme, in the investigated scenario it is assumed that each base station serve one user on the edge of its own cell and it shares the same bandwidth with neighbouring base station. The remainder of this chapter is organised as follows. Section 3.2 presents the system and channel models, parameters used throughout the chapter, and background of the problem addressed. Section 3.3 describes optimisation problem and three different scenarios investigated and methods used. Numerical results are discussed in section 3.4. Finally, section 3.5 summarises the conclusions of the proposed approach.

3.2 System Model of Two OFDMA-based Cellular Systems Covering a Common Area

Consider a scenario where two OFDMA-based cellular systems with two BSs covering different areas, having a common area in between. Assuming K users (edge users), with the index set $i, j = \{1, \cdots, K\}$, have been located at the edge of their own cell, far from BS antennas and within common area between aforementioned cells. This is shown in Fig. 3.1. K edge users coexists with each other in a specific frequency band. There are N OFDM sub-channels with the index set $n = \{1, \cdots, N\}$, all with bandwidth w, and each sub-channel experience flat-fading.

In this work, an interference-limited resource allocation method is developed where both edge-located users from different BSs are demanding specific levels of QoS defined by a threshold level of acceptable interference. BSs and mobile users are communicating point-to-point and relaying capability for these transmissions is not considered. In this method, both edge-located mobile users, who are willing to use the band, send information such as their QoS requirements

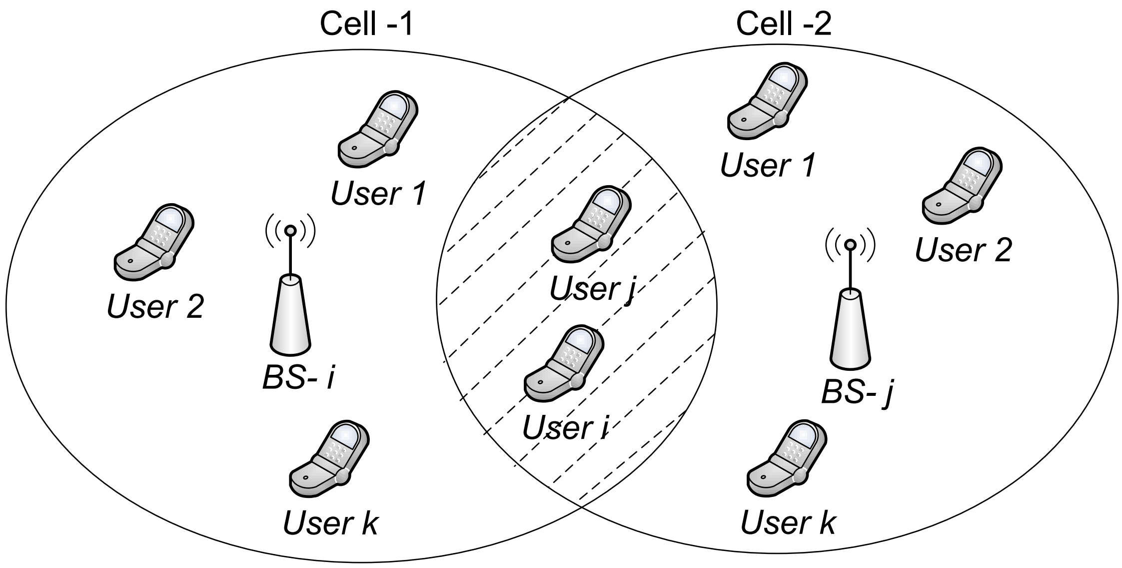

Figure 3.1: System Model

Cell-1 and Cell-2 Demonstrate Two OFDMA-based Cellular Systems with Two BSs Covering Different Areas and a Common Area Between Them.

and CSI to the BS of their own cell. Edge users inform the BS of their CSI, QoS requirements and power limitation in time periodic intervals prior to resource allocation for each period. The BS computes the allocated transmission based on user channel conditions and threshold level of acceptable interference. The CSI as well as power allocation results are exchanged between BS and users on dedicated signalling channel, accurately and instantly. The details of this signalling channel is out of scope of this chapter. It is also assumed that channel variations happen in intervals larger than resource allocation period. The channel power from BS-i to edge user i in sub-channel n is $h_{i,n}$ and the interference power from BS-j to edge user i, $i \neq j$, in sub-channel n is $g_{i,n}$. Both $h_{i,n}$ and $g_{i,n}$ are assumed to be stationary and ergodic with Probability Density Function (pdf)'s $f(h_{i,n})$ and $f(g_{i,n})$ respectively. Furthermore, channels are assumed to be Rayleigh fading, so the channel powers $h_{i,n}$ and interference powers $g_{i,n}$ are exponentially distributed. The same assumption is considered for user j of BS-j, with only the indexes changing from i to j. The received signal-to-interference-plus-noise ratio of user i from BS-i and user j from BS-j in sub-channel n can be written as

$$\begin{aligned} \gamma_{i,n} &= \frac{P_{i,n} h_{i,n}}{\sigma_{i,n}^2 + Q_{j,n} g_{j,n}}, \\ \gamma_{j,n} &= \frac{Q_{j,n} h_{j,n}}{\sigma_{j,n}^2 + P_{i,n} g_{i,n}}, \end{aligned} \tag{3.1}$$

where $P_{i,n}$, and $Q_{j,n}$ are the transmitted power, $\sigma^2_{i,n}$, and $\sigma^2_{j,n}$ are the Power Spectral Density (PSD) of Additive White Gaussian Noise (AWGN) for user i of BS-i and user j of BS-j in sub-channel n. It is assumed that the noise PSD is the same in all sub-channels for any user, that is, $\sigma^2_{i,n} = \sigma^2_{j,n} = \sigma^2$ for $i, j = 1, \cdots, K$, and $n = 1, \cdots, N$, without loss of generality. Links between users, direct channel powers, $h_{i,n}$, and $h_{j,n}$, also interfering interference powers $g_{i,n}$, and $g_{j,n}$ are assumed to be asymmetrical where they are different for different sub-channels.

3.3 Optimisation Problem and Methods

Here a resource allocation scheme is developed to maximise the sum rates of two users, $K = 2$, located in common area within two cells, while limiting the received interference level of each user. It must be noted that there is no priority between edge users (there is no primary and secondary system) and both of them have same opportunity for transmitting the signal. The threshold for the acceptable interference level is allowed to be different and it is based on service provider QoS requirement. Later in this chapter, it is shown that the best performance is achievable where acceptable interference level is identical for both users, and both users have the same QoS requirement.

3.3.1 Scenario 1: Two Sub-channels OFDMA-based System

Firstly an OFDMA-based cellular system is considered, each user having only two sub-channels ($N = 2$). This is shown in Fig. 3.2. Later in this chapter, the results obtained from two sub-channels scenario will be extended to the N sub-channels case where $N > 2$. As mentioned earlier in this chapter, the aim is maximising the sum rate of two interfering users while limiting the received interference at each user. Considering this and taking the equation 3.1 into account, the aim is to solve the following optimisation problem

$$\begin{aligned}
&\max_{P_{i,n}Q_{j,n}} \{R_T\} = \\
&\max_{P_{i,n}Q_{j,n}} \quad \log_2\left(1 + \frac{P_{1,1}h_{1,1}}{\sigma^2 + Q_{2,1}g_{2,1}}\right) \\
&\qquad + \log_2\left(1 + \frac{P_{1,2}h_{1,2}}{\sigma^2 + Q_{2,2}g_{2,2}}\right) \\
&\qquad + \log_2\left(1 + \frac{Q_{2,1}h_{2,1}}{\sigma^2 + P_{1,1}g_{1,1}}\right) \\
&\qquad + \log_2\left(1 + \frac{Q_{2,2}h_{2,2}}{\sigma^2 + P_{1,2}g_{1,2}}\right),
\end{aligned} \tag{3.2}$$

subject to

$$\begin{aligned}
&P_{1,1}g_{1,1} + P_{1,2}g_{1,2} \leq \tau_A, \\
&Q_{2,1}g_{2,1} + Q_{2,2}g_{2,2} \leq \tau_B,
\end{aligned} \tag{3.3}$$

where τ_A, and τ_B are the threshold level of interference for user i, and user j. Note that the interference limit is on the total received interference from all sub-channels. Any sub-channel with non-zero power allocation for a specific user is allocated to that user.

Considering the constraints in (3.3), the optimal power allocation that maximises (3.2) is found by using Lagrangian dual function $L(P_{i,n}, Q_{j,n}, \lambda_A, \lambda_B)$, where λ_A, and λ_B are the Lagrangian multiplier. It must be noted that because of convexity of this problem using the Lagrangian multipliers method following by Karush-kuhn-Tucker (KKT) conditions [42] is reasonable.

Optimising over $P_{1,1}$, $P_{1,2}$, $Q_{1,1}$, and $Q_{1,2}$ given λ_A, and λ_B yields

$$\begin{aligned}
&\frac{\partial L}{\partial P_{1,1}} = 0, \quad \frac{\partial L}{\partial P_{1,2}} = 0, \quad \frac{\partial L}{\partial Q_{2,1}} = 0, \quad \frac{\partial L}{\partial Q_{2,2}} = 0,\\
\Rightarrow \quad & P^*_{1,1} = \frac{1}{\lambda_A g_{1,1} \ln 2} - \frac{\sigma^2 + Q_{2,1} g_{2,1}}{h_{1,1}},\\
& P^*_{1,2} = \frac{1}{\lambda_A g_{1,2} \ln 2} - \frac{\sigma^2 + Q_{2,2} g_{2,2}}{h_{1,2}},\\
& Q^*_{2,1} = \frac{1}{\lambda_B g_{2,1} \ln 2} - \frac{\sigma^2 + P_{1,1} g_{1,1}}{h_{2,1}},\\
& Q^*_{2,2} = \frac{1}{\lambda_A g_{2,2} \ln 2} - \frac{\sigma^2 + P_{1,2} g_{1,2}}{h_{2,2}}.
\end{aligned} \tag{3.4}$$

Lagrangian multipliers, λ_A, and λ_B derived as

$$\begin{aligned}
\lambda^*_A &= \frac{2}{\left(\frac{(\sigma^2 + P_{1,1} g_{1,1}) g_{2,1}}{h_{2,1}} + \frac{(\sigma^2 + P_{1,2} g_{1,2}) g_{2,2}}{h_{2,2}} + \tau_B\right) \ln 2},\\
\lambda^*_B &= \frac{2}{\left(\frac{(\sigma^2 + Q_{2,1} g_{2,1}) g_{1,1}}{h_{1,1}} + \frac{(\sigma^2 + Q_{2,2} g_{2,2}) g_{1,2}}{h_{1,2}} + \tau_A\right) \ln 2}.
\end{aligned} \tag{3.5}$$

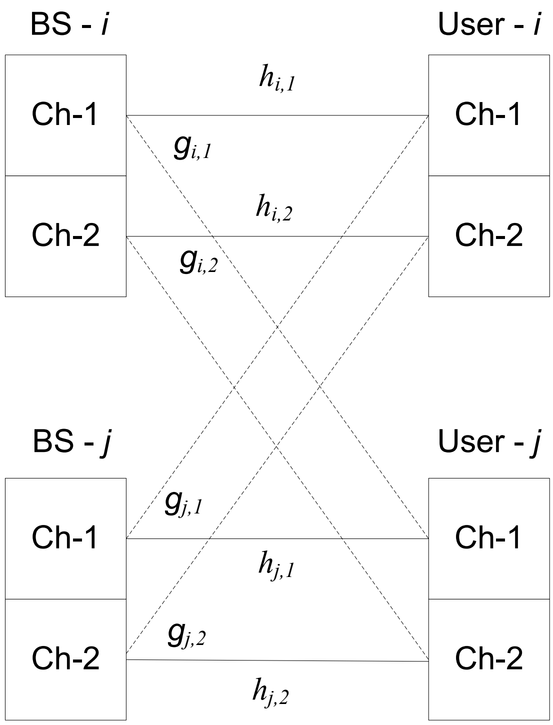

Figure 3.2: Two Sub-channels OFDMA-based System

An OFDMA-based Cellular System where Each User has Two Sub-channels ($N = 2$).

3.3.2 Scenario 2: N Sub-channel OFDMA-based System

In this section a situation similar to Scenario 1 is investigated, where users located at edge of their own cells and within common area of two cells have more than two sub-channels ($N > 2$). This is shown in Fig. 3.3. The optimisation problem becomes

$$\max_{P_{i,n}Q_{j,n}} \quad \sum_{n=1}^{N} \log_2\left(1+\frac{P_{i,n}h_{i,n}}{\sigma^2+Q_{j,n}g_{j,n}}\right) + \sum_{n=1}^{N} \log_2\left(1+\frac{Q_{j,n}h_{j,n}}{\sigma^2+P_{i,n}g_{i,n}}\right), \tag{3.6}$$

subject to

$$\begin{aligned} &\sum_{n=1}^{N} P_{i,n}g_{i,n} \le \tau_A, \quad \forall i \in \{1,2,\cdots,K\}, \\ &\sum_{n=1}^{N} Q_{j,n}g_{j,n} \le \tau_B, \quad \forall j \in \{1,2,\cdots,K\}. \end{aligned} \tag{3.7}$$

Considering the constraints in (3.7), the optimal power allocation that maximises (3.6) is found by using Lagrangian dual function $L(P_{i,n}, Q_{j,n}, \lambda_A, \lambda_B)$. The Lagrangian function and the KKT conditions for this problem are given in

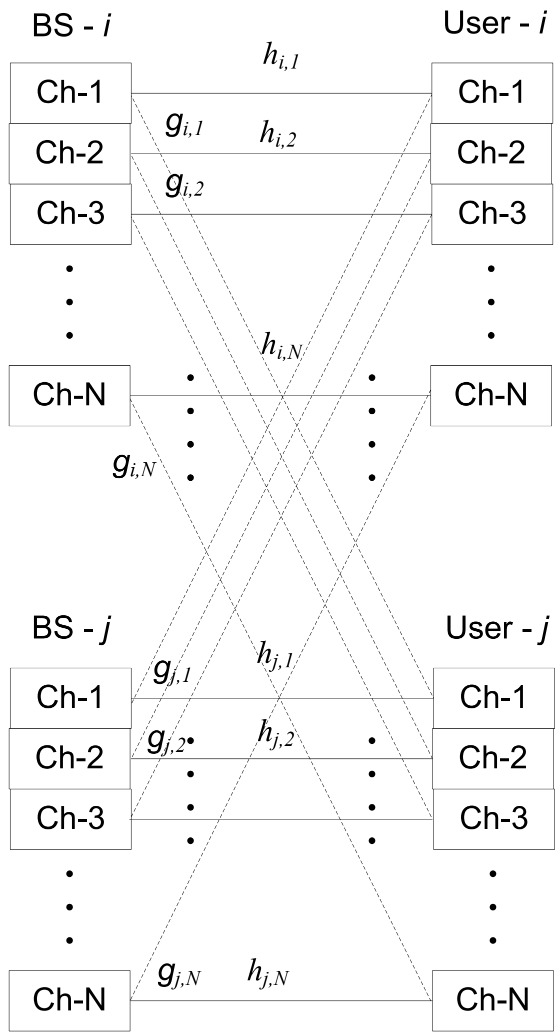

Figure 3.3: N Sub-channel OFDMA-based System

An OFDMA-based Cellular System where Each User has more than Two Sub-channels ($N > 2$).

$$
\begin{aligned}
L(P_{i,n}, Q_{j,n}, \lambda_A, \lambda_B) = & \sum_{n=1}^{N} \log_2 \left(1 + \frac{P_{i,n} h_{i,n}}{\sigma^2 + Q_{j,n} g_{j,n}}\right) \\
& + \sum_{n=1}^{N} \log_2 \left(1 + \frac{Q_{j,n} h_{j,n}}{\sigma^2 + P_{i,n} g_{i,n}}\right) \\
& - \lambda_A \left(\sum_{n=1}^{N} P_{i,n} g_{i,n} - \tau_A\right) \\
& - \lambda_B \left(\sum_{n=1}^{N} Q_{j,n} g_{j,n} - \tau_B\right),
\end{aligned} \tag{3.8}
$$

$$
\frac{\partial L}{\partial P_{i,n}} = 0, \quad \frac{\partial L}{\partial Q_{j,n}} = 0, \tag{3.9}
$$

$$
\lambda_A \left(\sum_{n=1}^{N} P_{i,n} g_{i,n} - \tau_A\right) = 0, \tag{3.10}
$$

$$
\lambda_B \left(\sum_{n=1}^{N} Q_{j,n} g_{j,n} - \tau_B\right) = 0, \tag{3.11}
$$

where $\lambda_A \geq 0$, and $\lambda_B \geq 0$. Optimising with respect to $P_{i,n}$, $Q_{j,n}$, yields

$$
\begin{aligned}
P_{i,n}^* &= \frac{1}{\lambda_A g_{i,n} \ln 2} - \frac{\sigma^2 + Q_{j,n} g_{j,n}}{h_{i,n}}, \\
Q_{j,n}^* &= \frac{1}{\lambda_B g_{j,n} \ln 2} - \frac{\sigma^2 + P_{i,n} g_{i,n}}{h_{j,n}}.
\end{aligned} \tag{3.12}
$$

with Lagrangian multipliers, λ_A, and λ_B derived as

$$\lambda_A^* = \frac{N}{\left(\sum_{n=1}^{N} \frac{g_{j,n}}{h_{j,n}}(\sigma^2 + P_{i,n}g_{i,n}) + \tau_B\right)\ln 2},$$
$$\lambda_B^* = \frac{N}{\left(\sum_{n=1}^{N} \frac{g_{i,n}}{h_{i,n}}(\sigma^2 + Q_{j,n}g_{j,n}) + \tau_A\right)\ln 2}. \tag{3.13}$$

3.3.3 Scenario 3: Best Channel Conditions Sub-Channel Selection

In this scenario, similar to scenario one, users located at edge of their own cells and within common area of two cells have two sub-channels. However, sub-channels are selected based on their channel conditions at each time. Compared to aforementioned scenarios, in which they employ a resource allocation scheme to maximise the sum rates of two users, no resource allocation method and constraints has been considered in this experiment. Any two sub-channels, with best channel conditions at that moment, out of totally four sub-channels that users have, will be selected for transmission. There will be four possible sets of sub-channels ((sub-ch1,sub-ch2), (sub-ch2,sub-ch3), (sub-ch1,sub-ch4), (sub-ch3,sub-ch4)) at each specific time. This method does not guarantee a maximised sum rate for two users and it is only based on best channel conditions. However, this may lead to a maximised sum rate for users. The comparison of numerical results and average spectral efficiency between this method, scenario 3.3.2, scenario and 3.3.1 is discussed in section 3.4.

3.4 Simulation and Numerical Results

In this section, the characteristics of the proposed resource allocation technique, through extensive simulations, is investigated. All the simulations are implemented using MATLAB R2010a. For this purpose, a simple case comprising only two users with two sub-channels located in common area of two neighbouring cooperative cells is studied. As mentioned in sub-section 3.3.2, the optimisation problem is then extended to N-sub-channels scenario in case there are many sub-channels. For the purpose of work in this chapter, it is assumed that there are only two users ($K = 2$) within common area of two cells. However, this can be extended as a future work to the case where there are more than two users ($K > 2$). Also, in these numerical examples, it is assumed that all the involved channels (i.e., the direct links, and the interference links) are Rayleigh distributed. Consequently, the channel power gains for these channels are exponentially distributed. Since the channel power gains can be different for different channel realisations, all the numerical results presented in this part are obtained by averaging over $1,000$ independent simulation runs. The average channel power gain for user i direct links are assumed to be 1.9, i.e. $E\{h_{i,n}\} = 1.9$, and for user j, $E\{h_{j,n}\} = 1$, $\forall n$. The average channel power gain for user i, and user j interference links are assumed to be $E\{g_{i,n}\} = 0.45$, and $E\{g_{j,n}\} = 0.5$ respectively, $\forall n$. Moreover, it is assumed that number of sub-channels N of the both systems are 256. The noise power on each sub-channel is also assumed to be identical, and equal to -50 dB, i.e. $\sigma^2 = -50$ dB. Considering that user i has better channel power gain than user j in overall, the effect of the interference threshold levels (τ_A, and τ_B) on power allocations is studied in Fig. 3.4, where the threshold levels for user i and j have been varied from -5 dB to 20 dB. As it is mentioned before, it is assumed that threshold levels for both users are identical and they are changing at the same rate, i.e. τ_A=τ_B. It is clear that as user i has better channel conditions than user j, the average allocated power for user i at same threshold level is higher than user j. The interference threshold levels for simulation results shown in Fig. 3.5, Fig. 3.6, and Fig.3.7 have been selected as τ_A=τ_B=10 dB. The effects of allocated power to the users on achievable rates based on these allocations, are plotted in Fig. 3.5. Here, average allocated power to user i, and j vary from -5 dB to 20 dB, both with same rate. The aim of the proposed resource allocation scheme is to limit the received interference, and referring to the plotted results in Fig. 3.6, and Fig.3.7 shows that limiting receive interference assures that users located near cell edges and within common area of two cells can maintain a certain level of throughput. As user i is assumed to have better channel conditions than user j, more power (Fig. 3.4), thereby a higher data rate is allocated to user i.

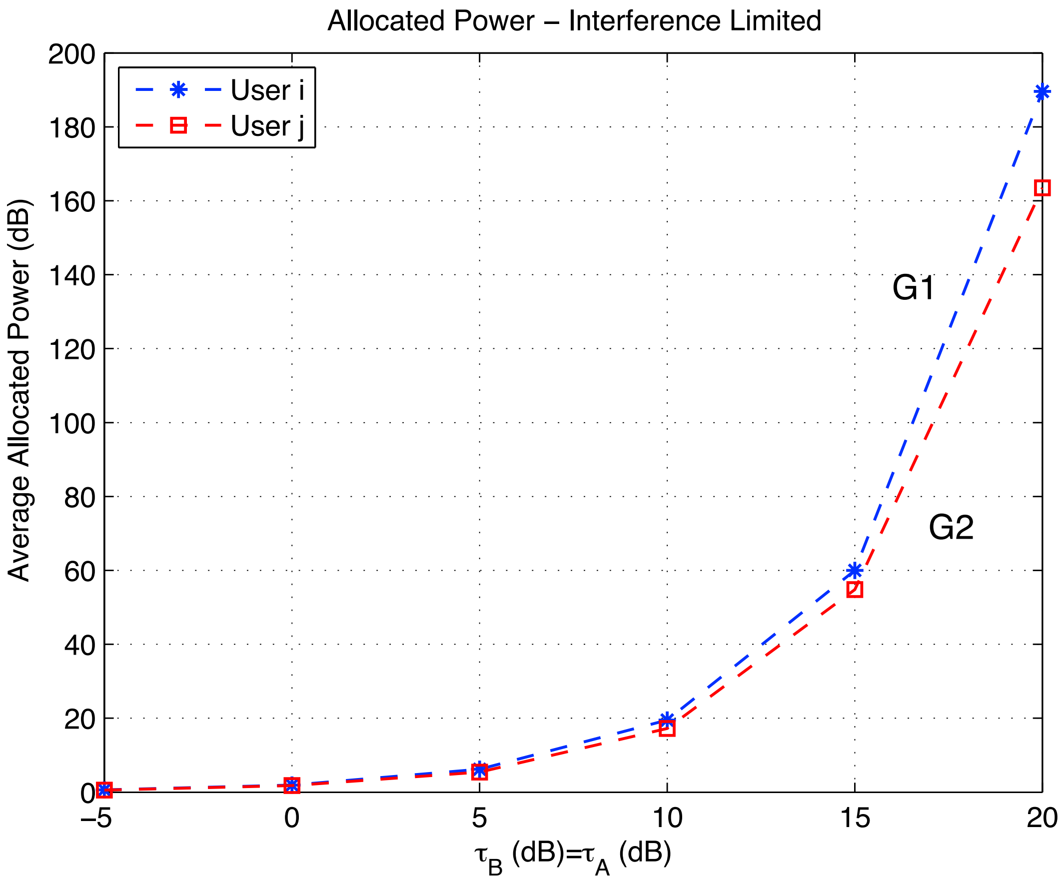

Figure 3.4: Average Allocated Power

G1: Average Allocated Power for User i.
G2: Average Allocated Power for User j.

In the current OFDM system such as in the IEEE 802.11a/g standard, the Media Access Control (MAC) layer provides two different wireless access mechanisms for wireless medium sharing, namely, the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). The DCF achieves automatic medium sharing among users using carrier sense multiple access with collision avoidance and request to send/clear to send. The PCF is a more centralised control mechanism. In both mechanisms, TDMA technology is utilised for all users to share the channels. Similarly, in the 3.6 non-cooperative TDMA, it is assumed that, at each time, only one user occupies all the bandwidth. This is also optimal for TDMA over the single-cell case due to severe interference [3]. In OFDM networks, each user has the flexibility to assign the transmission over different subcarriers. This flexibility gives the possibility of cooperation among users. In a TDMA system without relays, if a terminal does not have a packet to transmit, its time slot remains idle, i.e. the slot becomes a wasted channel resource. In Fig. 3.6, the cooperative interference-limited OFDM system over TDMA is considered by using this flexibility. At each time, still, only one user transmits with positive power. However, this user can select the number of subcarriers for its own data while keeping the same rate by using adaptive modulation and power control. At the same time, this user can determine the number of subcarriers for relaying parts of others data. The analysis reveals significant performance gains of the cooperative OFDM strategies over their non-cognitive counterparts. This is because the described cognitive strategies do not result in any bandwidth loss, as cooperation is enabled only in idle unused channel resources, which results in a graceful degradation of the maximum stable throughput when increasing the communication rate [43]. In Fig. 3.6 the achieved average spectral efficiency of proposed interference power constraint resource allocation scheme is compared with achieved average spectral efficiency by non-cooperative TDMA.

Non-cooperative TDMA average spectral efficiency is the average spectral efficiency that it is achievable for both users without considering any interference and taking to the account that at each time instant, only one BS is able to transmit signals to the edge user. Furthermore, in non-cooperative TDMA case there is no incorporation for the dominant interference effects of the neighbouring cells within the received interference level. It can be observed from Fig. 3.6 that interference power constraint scheme outperforms non-cooperative TDMA case. In addition, the gain of this scheme over TDMA is wider at low allocated power region as at high allocated power region, too much interference is allowed.

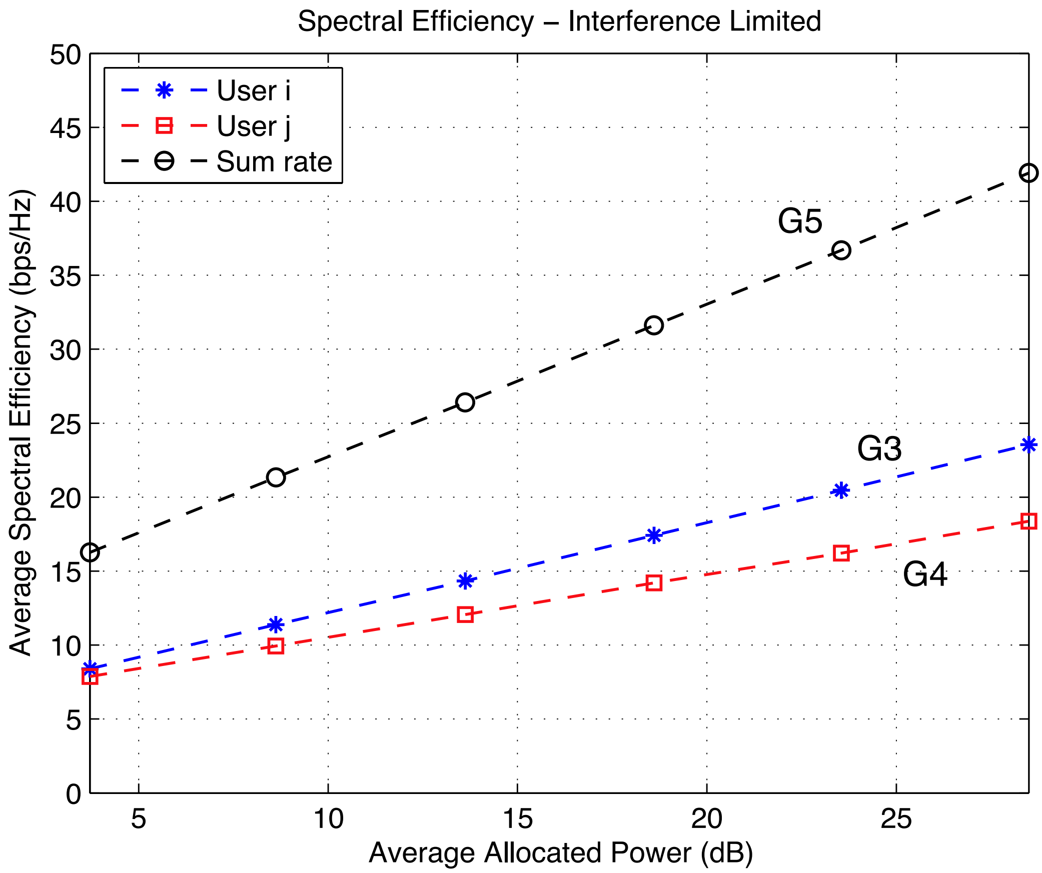

Figure 3.5: Spectral Efficiency vs Average Allocated Power to Users

G3: Average Spectral Efficiency for User i.
G4: Average Spectral Efficiency for User j.
G5: Sum Rate of Two Users.

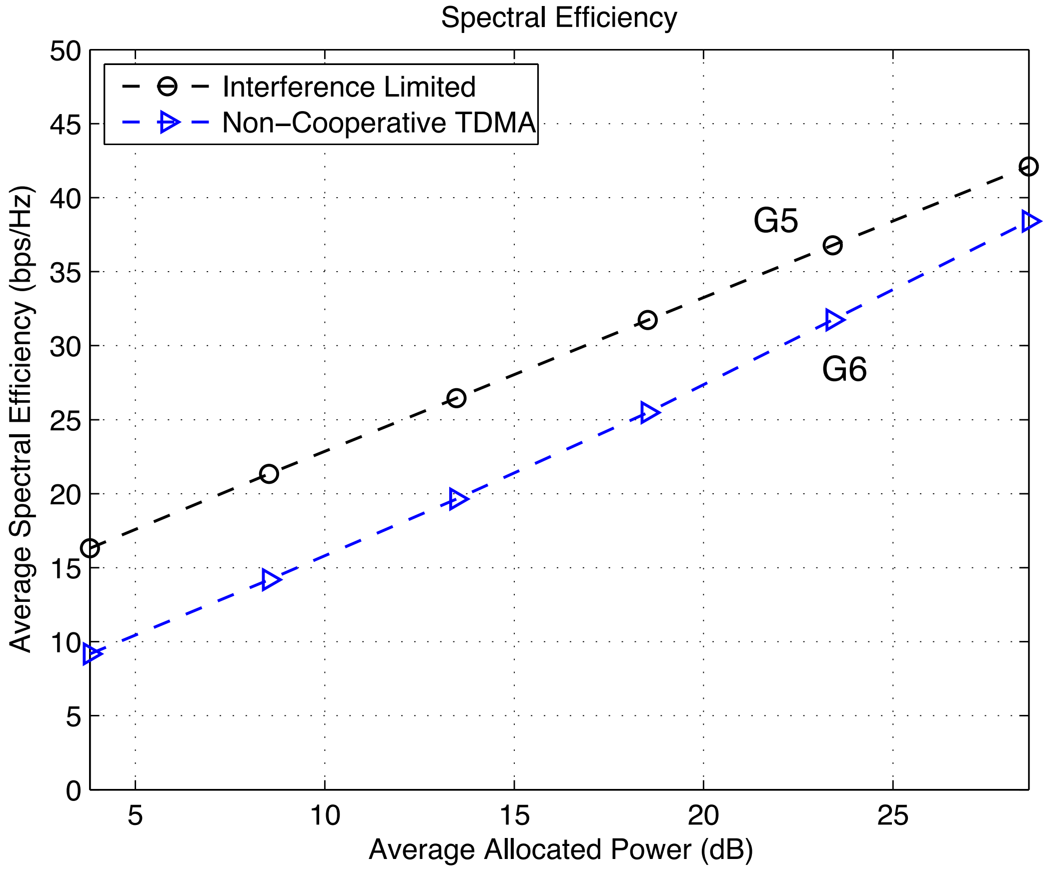

Figure 3.6: Average Spectral Efficiency vs Average Allocated Power

G5: Average Spectral Efficiency for Interference Limited Method (Sum Rate of Two Users).
G6: Average Spectral Efficiency for Non-Cooperative TDMA Method (Sum Rate of Two Users).

In Fig. 3.7, the achieved average spectral efficiency of scenario 3.3.3 is compared with other scenarios, in which they employ resource allocation schemes (interference limited and power limited) and QoS requirements based on user channel conditions (τ_B/τ_A), to maximise the sum rates of two users.

Fig. 3.7 confirms within these three schemes, power limited solution performs better with a $3bps/Hz$ difference. However, it must be noted that power limited scheme does not consider the channel interference conditions as opposed to the other two scenarios (interference-limited or dynamic interference threshold level). In the dynamic interference threshold level, QoS requirements is considered and it is formulated as

$$\tau_B/\tau_A = K(h_3 + h_4)/(h_1 + h_2) \tag{3.14}$$

This shows that user with a better channel condition allows a greater threshold level of interference in the interference-limited scenario and a poor channel condition will limit the interference threshold more. Fig.3.7 also confirms that having a dynamic interference threshold level preforms around 1-2 bps/Hz better than when a static interference threshold level is considered.

Fig. 3.7 confirms that employing resource allocation scenarios have much better average spectral efficiency at the same average allocated power compared

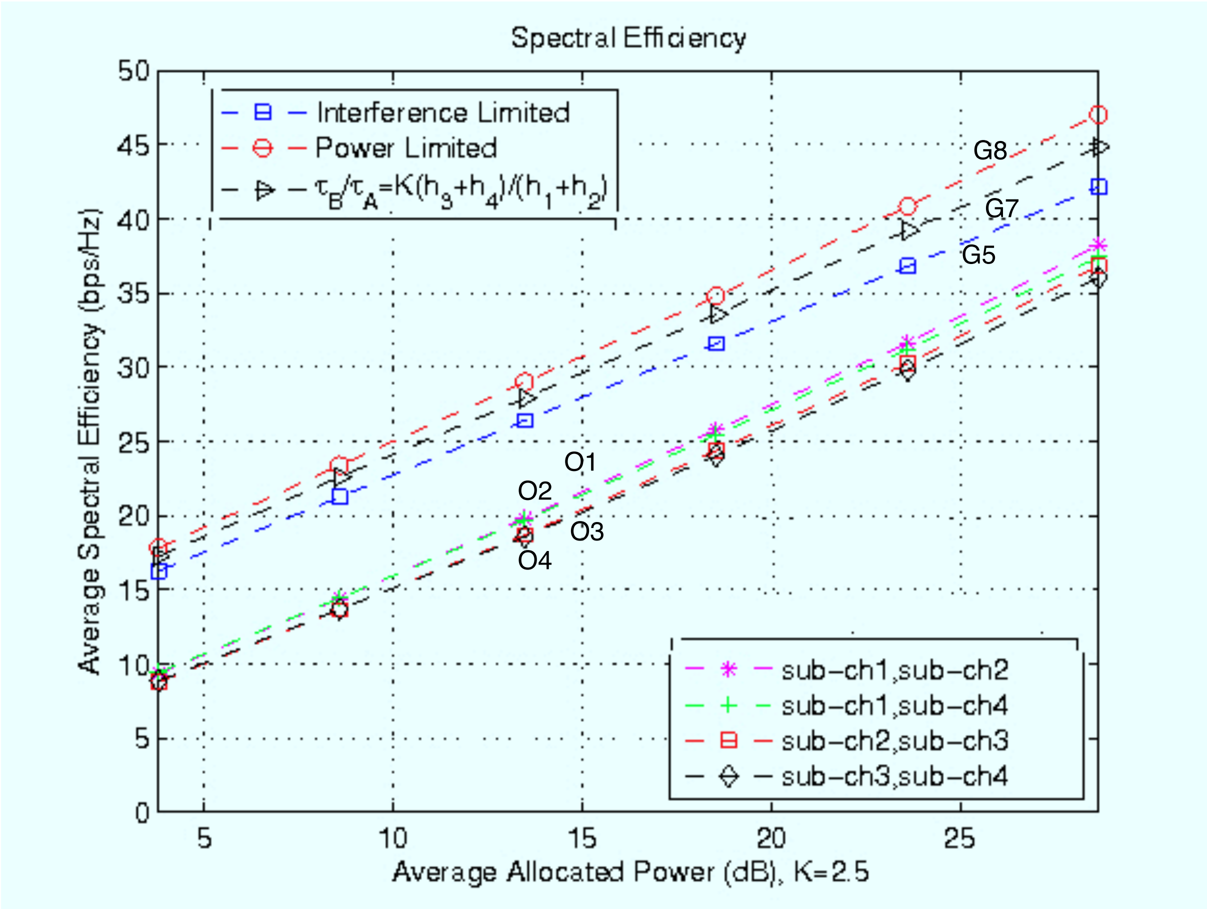

Figure 3.7: Comparison of Average Spectral Efficiency vs Average Allocated Power, of Different Methods

G5: Interference Limited
G7: $\tau_B/\tau_A = K^{(h_3+h_4)}/(h_1+h_2)$
G8: Power Limited
O1: sub-ch1,sub-ch2
O2: sub-ch1,sub-ch4
O3: sub-ch2,sub-ch3
O4: sub-ch3,sub-ch4

to sub-channel selection based on best channel conditions of sub-channels. This difference in average spectral efficiencies is around $9bps/Hz$.

3.5 Summary

Maximising the sum rate of two interfering users, while limiting the received interference at each user, in an OFDMA-based system with cooperating BSs, operating in downlink, is analysed in this chapter. In a cooperative two cell scenario, for each particular user (located in the edge of the cooperative cells and within the common area of the neighbouring cells), it is possible to incorporate the dominant interference effects of the neighbouring cells within the received noise level. Firstly the two sub-channels scenario, for two users located in their own cell edges and within the common area of the cooperating cells, is investigated. Then, the proposed two sub-channels scenario is extended to a N sub-channel scenario. Moreover, the optimal power allocation strategy to maximise the sum rate of two edge users, subject to interference power constraint, is derived. It is shown that the interference power constraint resource allocation scheme can achieve excellent levels of efficiency by allocating resources more intelligently. Results prove that the proposed cooperative BSs scheme outperforms the non-cooperative TDMA method.

As a future work, the proposed approach can be extended to a scenario where there are more than two users on the edge of neighbouring cells and also adjusting the interference threshold level according to the channel conditions. Although it needs to be clarified that, practically, extension of the proposed approach to a model with more than two edge users will not be a straightforward process. The complexity of this extension is due to the challenge that the optimisation problem stated in the equation 3.2 needs to be adjusted to accommodate more than two edge users. Also the number of constrains of the problem will grow per number of edge users assuring to consider a threshold level of interference for each user.

Chapter 4

Statistical Approach for Event Region Detection in Wireless Sensor Networks

4.1 Overview of Event and Boundary Detection in WSNs

WSNs consist of a set of low-cost, low-power, multifunctional nodes that are able to interact with their environment by sensing physical parameters. These nodes collaborate to fulfil their tasks using wireless communication and are a promising technology for remotely detecting physical phenomena such as forest fires, chemical leaks and radioactive clouds. The vast application of WSNs has encouraged researchers to examine various aspects of WSNs in search for more efficient and robust systems. In many applications, the main task of WSNs is to monitor, detect and report the occurrence of events. An event can be defined as an exceptional change in environmental parameters such as temperature, pressure, humidity, etc. With an emerging need in environmental monitoring, research on event-region detection problems in WSNs has recently become a topic of great interest. Such problems arise in many scenarios; for example, as part of a building's safety system, a WSN may be used to monitor hot spots and smoke. Also, using a WSN to sense the concentration of chemicals can identify which regions have a chemical concentration greater than some threshold [44]. In event-detection problems, sensor networks are asked to determine where regions or boundaries in the environment are by analysing distinguishable collected attributions of the monitored area [45]. However, in some cases the detection of event boundary can be more efficacious than detection of the entire event region, e.g. in forest-fire and chemical-spill scenarios wherein events span a particular geographic region [46].

The problem of boundary detection and region detection has been considered in the recent literature. Ding and Cheng [47] propose an algorithm for detecting event-boundary sensors based on statistical mixture methods with model selection. A statistical approach to distributed edge-sensor detection is introduced in [33] and [48] where the objective is to determine whether a target sensor is located in the edge area of a certain phenomenon or not based on data from its neighbouring sensors. Nowak and Mitra [49] proposed an edge-estimation scheme when there exists a predefined hierarchical structure within the sensor network. Later, Chintalapudi and Govindan introduced three approaches to distributed edge sensor detection: statistical, filter and classifier-based [50].

In this chapter, a network of spatially distributed and wirelessly connected sensor nodes monitoring an area of interest is considered, this network is commissioned to detect two different phenomenas occurring in distant parts of this area. In general, the required bandwidth to transmit entire readings from all nodes to the base station for further processing is proportional to the size of the entire network. However, if only the nodes placed in the close-by region of each phenomena report back their reading to the base station, the required bandwidth reduces to be proportional to the size of that event-region only. With bandwidth being a major resource constraint in WSN systems, the latter is a more promising approach.

As illustrated in Fig. 4.1, each sensor node in the area is asked to acknowledge whether it associates with one of the two event regions or if it is a non-event region node. In this proposed approach, each node employs only its own environmental readings from two (live) events to make this decision. The readings generated by event alarming signals and more specifically the statistical parameters of the received signal distribution at each node is used for this purpose. This algorithm suggests distinguishable differences for collected attributes of nodes positioned inside event regions compared to those positioned outside event regions. This approach enables nodes to decide if their received signal has mainly resulted from one event message or if it is proportionally generated by both broadcasted alarms.

The remainder of this chapter is organised as follows. The proposed algorithm and network model is introduced in section 4.2. Section 4.3 presents the numerical and simulation results for this problem and finally 4.4 summarises the conclusions of the proposed approach.

4.2 Proposed Algorithm and Network Model

Consider a WSN composed of n spatially distributed nodes aiming to detect two distinctive events over an area of interest. When an event occurs, it broadcasts

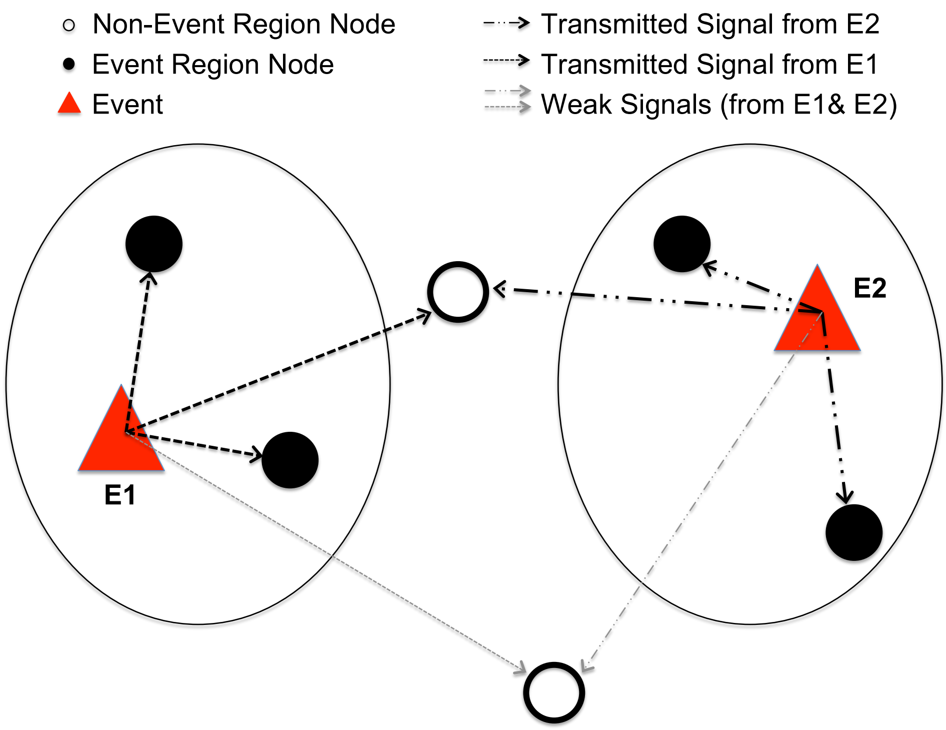

Figure 4.1: Event Region and Non-event Region Nodes

E1: Event 1
E2: Event 2

a constant power signal to its surrounding area. If the two events assumed to be active simultaneously, then all the nodes in this area receive signals from both live events. The proposed algorithm here suggests a solution for classifying these nodes into two distinctive categories based on their received signal attributes. An event-region category is defined as the domain surrounding one single event and comprising those nodes whose received signal is mainly generated by that event signal. Evidently, nodes receiving a mixed signal resulted from two event signals and those receiving a very weak signal (due to path-loss and fading) are categorised as a non-event region. As mentioned, upon activation, each event emits a signal. However, the transmitted signals weaken throughout the transmission channel due to attenuation impacts such as path-loss and fading. This means the strength of the received signal from each event differs in various locations of the monitoring area. While in theory each sensor's reading is comprised of both transmitted signals, the intuitive conclusion suggests a distinguishable difference in collected attributes of received signals for nodes inside the event region compared to those outside it. The proposed algorithm claims that for those nodes placed in one event-region, received signal power is more likely to result from only one event message. For those lying between two region boundaries, the received signal is believed to be composed proportionally from both alarm messages. The proof of this proposal leads to a new approach distinguishing between event-region and non event-region nodes. In other words, the developed algorithm enables differentiation between nodes placed inside an homogeneous event-region and those lying within the boundaries of two heterogenous regions. To address this problem a binary-hypothesis test is set

- H_0: Target sensor is a bi-reading sensor
- H_1: Target sensor is a single-reading sensor

A node is called bi-reading if its received signal is composed proportionally from two event messages while a single-reading node receives signal mainly from one event. To assign each node to one of the mentioned hypotheses, the received signal power and more specifically its distribution attributes are analysed in this work.

When an event occurs, it broadcasts a signal to its surrounding areas. Due to a number of factors such as path-loss and fading the strength of this signal weakens throughout the transmission channel. Considering P_j to be the power transmitted by event j, in this scenario $j = 1, 2$, the power $p_{j,u}$ received from this event by a node u, $u = 1, ..., n$, is modelled as

$$p_{j,u} = P_j K d_{j,u}^{-\alpha} X_{j,u}, \tag{4.1}$$

where K is a constant value, d is the event-node (transmitter-to-receiver) distance, α is the path-loss exponent varying from 2 to 6 for different environment, and $X_{j,u}$ is fast fading effect for node u. In fact, $X_{j,u}$ is a random variable representing Rayleigh fading effects, whose pdf is $f_X(x; \lambda) = \lambda e^{-\lambda x}$ [51]. The idea is to analyse $p_{j,u}$ at each node and use the findings to set the hypothesis. Like any other statistical distribution, there are different methods to demonstrate $p_{j,u}$ distribution. Here, the pdf and its characteristics is used for the purpose of analysis. From (4.1), it can be seen that mainly two parameters influence the distribution of $p_{j,u}$. Assuming the transmitting power P_j to be constant, the pattern of $p_{j,u}$ is mainly down to path-loss and fast-fading parameters. As mentioned, the fast fading factor is in fact a random variable with exponential distribution. Therefore, the intuitive conclusion suggests $p_{j,u}$ should also follow exponential distribution when path-loss factor tends to one, i.e. when the transmitter-to-receiver distance is less than a certain threshold value. To prove this initial theory, the received signal power at one node is considered then its distribution is analysed with the aim to extract instructive information about its event-wise location. $p_{1,u}$ and $p_{2,u}$ indicate received signal power at node u respectively from event 1 and event 2 and are expressed by

$$p_{1,u} = P_1 K d_{1,u}^{-\alpha} X_{1,u}, \tag{4.2}$$

$$p_{2,u} = P_2 K d_{2,u}^{-\alpha} X_{2,u}. \tag{4.3}$$

Total received power at node u is resulted from addition of these two power, therefore

$$\begin{aligned} p_{total,u} &= p_{1,u} + p_{2,u}, \\ p_{total,u} &= P_1 K d_{1,u}^{-\alpha} X_{1,u} + P_2 K d_{2,u}^{-\alpha} X_{2,u}, \\ p_{total,u} &= K(P_1 d_{1,u}^{-\alpha} X_{1,u} + P_2 d_{2,u}^{-\alpha} X_{2,u}). \end{aligned} \tag{4.4}$$

Assuming the transmitting power P_j to be constant and since $d_{j,u}^{-\alpha}$ has a numeric value and with $a^{'}$, $b^{'}$, a, and b to be substitutions parameters, the following simplification is made

$$P_1 d_{1,u}^{-\alpha} = a^{'} \longrightarrow a^{'} K = a, \tag{4.5}$$

$$P_2 d_{2,u}^{-\alpha} = b^{'} \longrightarrow b^{'} K = b. \tag{4.6}$$

As a result, the expression (4.4) is re-written as

$$p_{total,u} = aX_{1,u} + bX_{2,u}. \tag{4.7}$$

Therefore, total received power at each node is sum of two weighted random variable where the coefficient a and b comprise the effect of path-loss. The parameters a and b are inversely proportional to corresponding transmitter-to-receiver distance

$$\begin{aligned} a &\propto (1/d_{1,u})^{\alpha}, \\ b &\propto (1/d_{2,u})^{\alpha}. \end{aligned} \tag{4.8}$$

In fact, the total received power at node u is a random variable itself and like any other random variable, there exists a pdf for it. To classify each node to one of the hypotheses, H_0 and H_1, this distribution is analysed and more specifically *skewness* of $p_{total,u}$ distribution is employed as the deciding parameter in this work. In statistics, skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable [52]. A zero value skewness indicates that the values are relatively evenly distributed on both sides of the mean, typically but not necessarily implying a symmetric distribution. The skewness of a random variable X is the third standardised moment given by

$$SK(X) = \frac{E[(X-\mu)^3]}{\sigma^3}, \tag{4.9}$$

where μ and σ are mean and standard deviation, respectively. As mentioned, the total received power at node u is a random variable so the skewness of its distribution can be derived by employing (4.9). In the following section, it is investigated whether there is a logical correlation between skewness of $p_{total,u}$ distribution and its respective event-node distance ratio.

4.2.1 Total Received Power Distribution and its Skewness

For the purpose of simplification and by making the following substitution

$Z = p_{total,u}, X_1 = X_{1,u}, and\ X_2 = X_{2,u}$ and by taking (4.7) into consideration

$$Z = aX_1 + bX_2, \tag{4.10}$$

and from expression (4.9)

$$SK(Z) = \frac{E[(Z-\mu_Z)^3]}{\sigma_Z^3} = \frac{E[(Z-\mu_Z)^3]}{E[(Z-\mu_Z)^2]^{\frac{3}{2}}}, \tag{4.11}$$

with further simplification

$$E[(Z-\mu_Z)^3] = a^3\mu^{\circ}_{3X_1} + b^3\mu^{\circ}_{3X_2},$$
$$E[(Z-\mu_Z)^2] = a^2\mu^{\circ}_{2X_1} + b^2\mu^{\circ}_{2X_2}, \tag{4.12}$$

where $\mu^{\circ}_{nX_j}$ indicates nth central moment for random variable X_j with the following definition

$$\mu^{\circ}_{nX_j} = E[(X_j - \mu)^n], \tag{4.13}$$

where

$$\mu = \mu_1 = E[X_j] = \ 1st \ \ moment \ \ of \ \ X_j. \tag{4.14}$$

Conversely, X_1 and X_2 are exponentially distributed with rate parameters λ_1 and λ_2 and their 2nd and 3rd central moments are as expressed in (4.16)

$$X_1 \sim Exp(\lambda_1) \quad X_2 \sim Exp(\lambda_2), \tag{4.15}$$

$$\mu^{\circ}_{3X_1} = \frac{2}{\lambda_1^3}, \qquad \mu^{\circ}_{3X_2} = \frac{2}{\lambda_2^3},$$
$$\mu^{\circ}_{2X_1} = \frac{1}{\lambda_1^2}, \qquad \mu^{\circ}_{2X_2} = \frac{1}{\lambda_2^2}. \tag{4.16}$$

From (4.11) and (4.12) and (4.16) the skewness of the total received power at node u is

$$SK(Z) = 2\frac{\left(\frac{a^3}{\lambda_1^3} + \frac{b^3}{\lambda_2^3}\right)}{\left(\frac{a^2}{\lambda_1^2} + \frac{b^2}{\lambda_2^2}\right)^{\frac{3}{2}}}. \tag{4.17}$$

By analysing (4.8) and (4.17) the impact of distance ratio on the distribution skewness can be derived.

However, for an individual exponential distribution

$$X_1 \sim Exp(\lambda_1), \tag{4.18}$$

$$SK(X_1) = \frac{E[(X_1 - \mu_{X_1})^3]}{E[(X_1 - \mu_{X_1})^2]^{\frac{3}{2}}}. \tag{4.19}$$

From (4.13) and (4.16):

$$\begin{aligned} SK(X_1) &= \frac{\mu^{\circ}_{3X_1}}{(\mu^{\circ}_{2X_1})^{\frac{3}{2}}} \\ &= \frac{\frac{2}{\lambda_1^3}}{\frac{1}{\lambda_1^2}^{\frac{3}{2}}} = 2. \end{aligned} \tag{4.20}$$

Interestingly, equation (4.20) proves that for an exponential distribution the skewness has a certain value: $SK(exp(\lambda)) = 2$. Considering this fact and looking back at (4.7), it is to be investigated for which range of a and b distribution of $p_{total,u}$ tends to or deviates from exponential distribution. Simulation results verify that various distance ratios will result in different skewness ranges. Each node is then classified to one of the hypotheses based on its distribution skewness range.

4.2.2 Required Number of Samples

To employ distribution as the deciding factor for the nodes' regional situation, it should be precise enough i.e. it should hold an adequate number of samples. This section discusses how many samples are needed to make such a distribution. To obtain this factor, a known statistical error named Standard Error of Skewness (SES) is employed. In general, the standard error is the standard deviation of the sampling distribution of a statistic [53]. Cramer presents a formula for SES in [54]

$$\mathrm{SES} = \sqrt{\frac{6 \times N \times (N-1)}{(N-2) \times (N+1) \times (N+3)}}. \tag{4.21}$$

where N indicates the number of samples. For example, for SES to be 0.05, the number of required samples is approximately 2400. Controversially, the simulation results for the proposed approach demand a totally different number of samples for the same value of error. The reason behind this noticeable difference is that expression (4.21) is only true for normal distribution while the simulation results of the proposed work are based on exponential distribution. Furthermore, Table 4.1 presents the required number of samples, N, for different SES values for exponential distribution based on simulation results.

Table 4.1: Simulation-Based Results for the Required Number of Samples, N, for Different SES Values for Exponential Distribution

N	15,000	20,000	30,000	100,000
SES	0.07	0.06	0.05	0.028

However expression (4.21) is not directly applicable for exponential distribution, but the above numeric results prove the pertinence of a modified version of this formula. The formula is true for all N and SES values in Table 4.1 by adding the same constant coefficient

$$\mathrm{SES}_{exp} = \xi \times \sqrt{\frac{6 \times N \times (N-1)}{(N-2) \times (N+1) \times (N+3)}}. \tag{4.22}$$

ξ is a numeric value adjusting the SES formula to be valid for exponential distribution.

In the next section, simulation and numerical results are discussed.

4.3 Simulation and Numerical Results

This section provides analysis on the distribution of total received power at each node, $p_{total,u} = aX_{1,u}+bX_{2,u}$, and more specifically on the changes in its skewness, as a statistical metric, resulting from applying various distance ratios $(\frac{d_{1,u}}{d_{2,u}})$ with respect to the two events. For this purpose, $X_{j,u}$ is assumed to be a random variable representing Rayleigh fading effects whose pdf is $f_X(x;\lambda) = \lambda e^{-\lambda x}$.

Furthermore, the eq. (4.17), representing the skewness of the total received power at node u, with respect to different distance ratios is illustrated in Fig. 4.4. Later on by comparing these results, the rules for a hypothesis test are discussed. Fig. 4.2, illustrates pdf of $p_{total,u}$ fitted to a standard exponential distribution, for four different distance ratios. The aim is to analyse the divergence/convergence of total received power 's distribution from the standard exponential distribution with respect to the change in distance ratio. From this graph, it is prominent that when a node u is distanced equally from both events, i.e. ratio=1, exponential distribution is not fitted to $p_{total,u}$. However, it can also be seen that for ratio, $\frac{d_{1,u}}{d_{2,u}} > 2$, distribution of $p_{total,u}$ starts to follow an exponential pattern, meaning the node u is significantly closer to one of the event.

On the other hand, as mentioned in section 4.2.1, for a standard exponential distribution skewness has a certain value of 2. In Fig. 4.3, the aim is to determine if a correlation exists between the distance ratio and the skewness range of $p_{total,u}$. The results in Fig. 4.3 also confirm that only for $\frac{d_{1,u}}{d_{2,u}}$ >2, again meaning that the node u is significantly closer to one of the event, the skewness range of $p_{total,u}$'s distribution is placed within a confidence interval of the skewness of standard exponential distribution (i.e. $2 - e \leq SK(p_{total,u}) \leq 2$). Here, e indicates the accepted error margin. Repeating this simulation for 30 times proves the major intensity of skewness range to be greater than 1.95 when

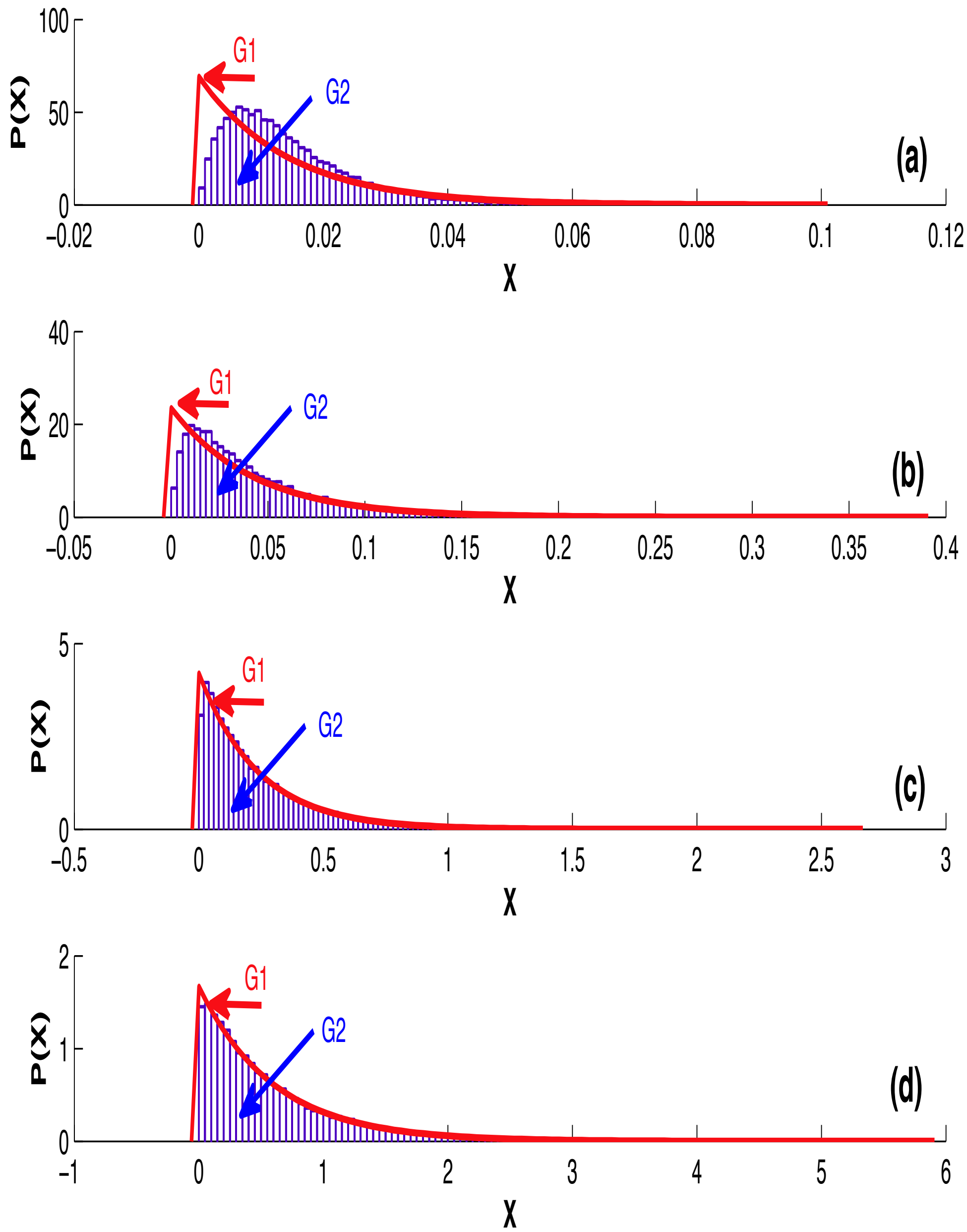

Figure 4.2: pdf of $p_{total,u}$ Fitted to pdf of a Standard Exponential Distribution for Different Distance Ratios

G1: pdf of Standard Exponential Distribution
G2: pdf of Total Received Power at Node u

(a) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=1

(b) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=2

(c) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=5

(d) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=8

distance ratio is greater than 2 which indicates a 5% margin error.

The following rule for a hypothesis test is derived from these simulation results

- H_1 is true if $2 - e \leq SK(p_{total,u}) \leq 2$: which means $node_u$ is an event-region node (single-reading sensor)
- H_0 is true otherwise: which means $node_u$ is not an event-region node (bi-reading sensor)

Additionally in this work, a mathematical closed form for calculating the skewness of the sum of two exponential random variables was produced and presented in (4.17). The graphs in Fig. 4.4 represent this closed form model with respect to the same four different distance ratios applied in the previous simulations. The result from this graph, confirm the rule set for the hypothesis test to stand true. Once more, it can be confirmed that as the distance ratio, $\frac{d_{1,u}}{d_{2,u}}$, increases the skewness range of $p_{total,u}$ sits in a more precise margin error with respect to the specified value of the standard exponential distribution's skewness (2).

4.4 Summary

In this chapter, event-region detection as one of major problems in the WSN field was studied. In the proposed scheme, a scenario where two different phenomena are present in distant parts of an area of interest were investigated. A hypothesis

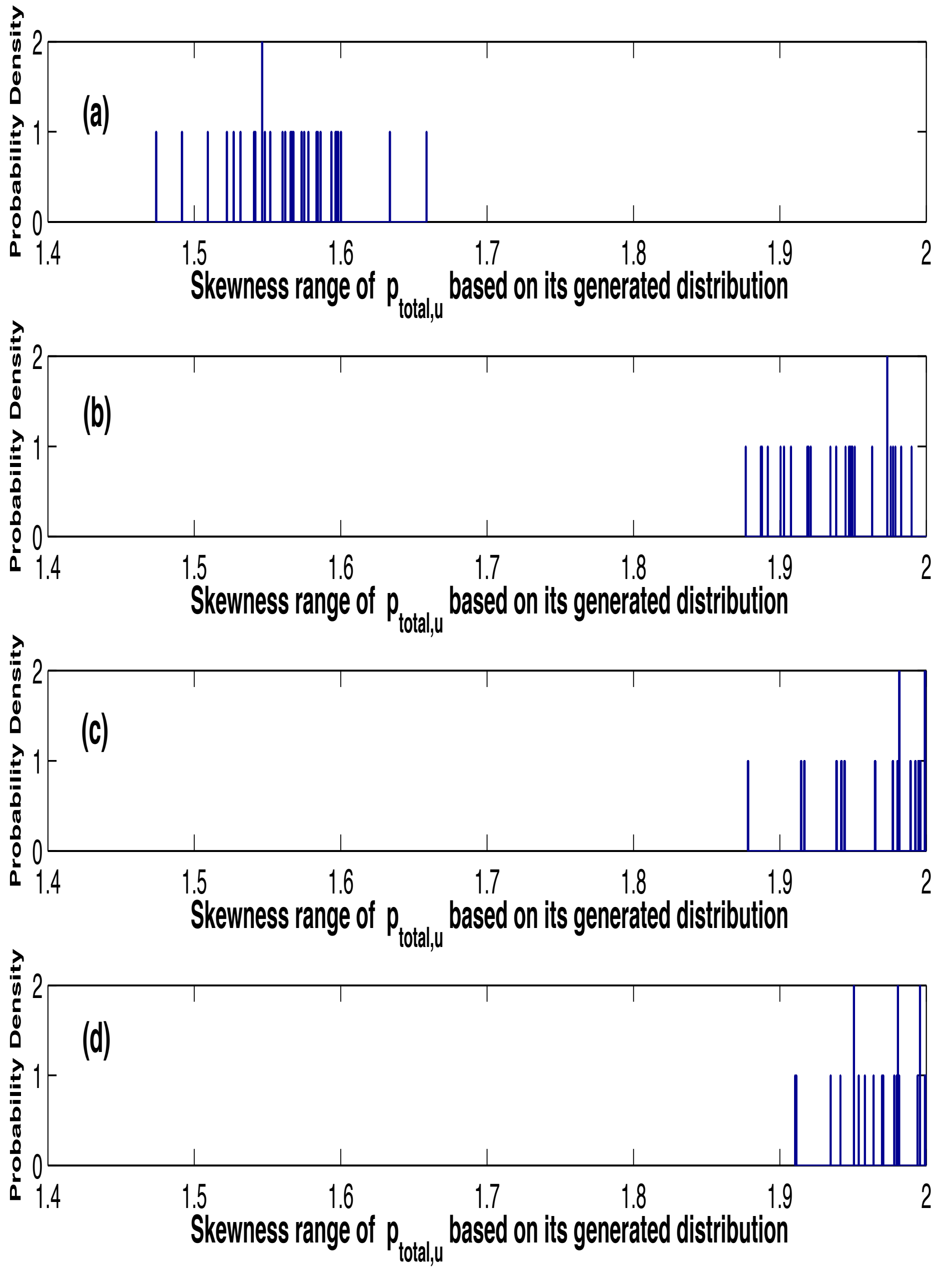

Figure 4.3: Skewness Range of $p_{total,u}$ for Different Distance Ratios

(a) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=1

(b) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=2

(c) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=5

(d) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=8

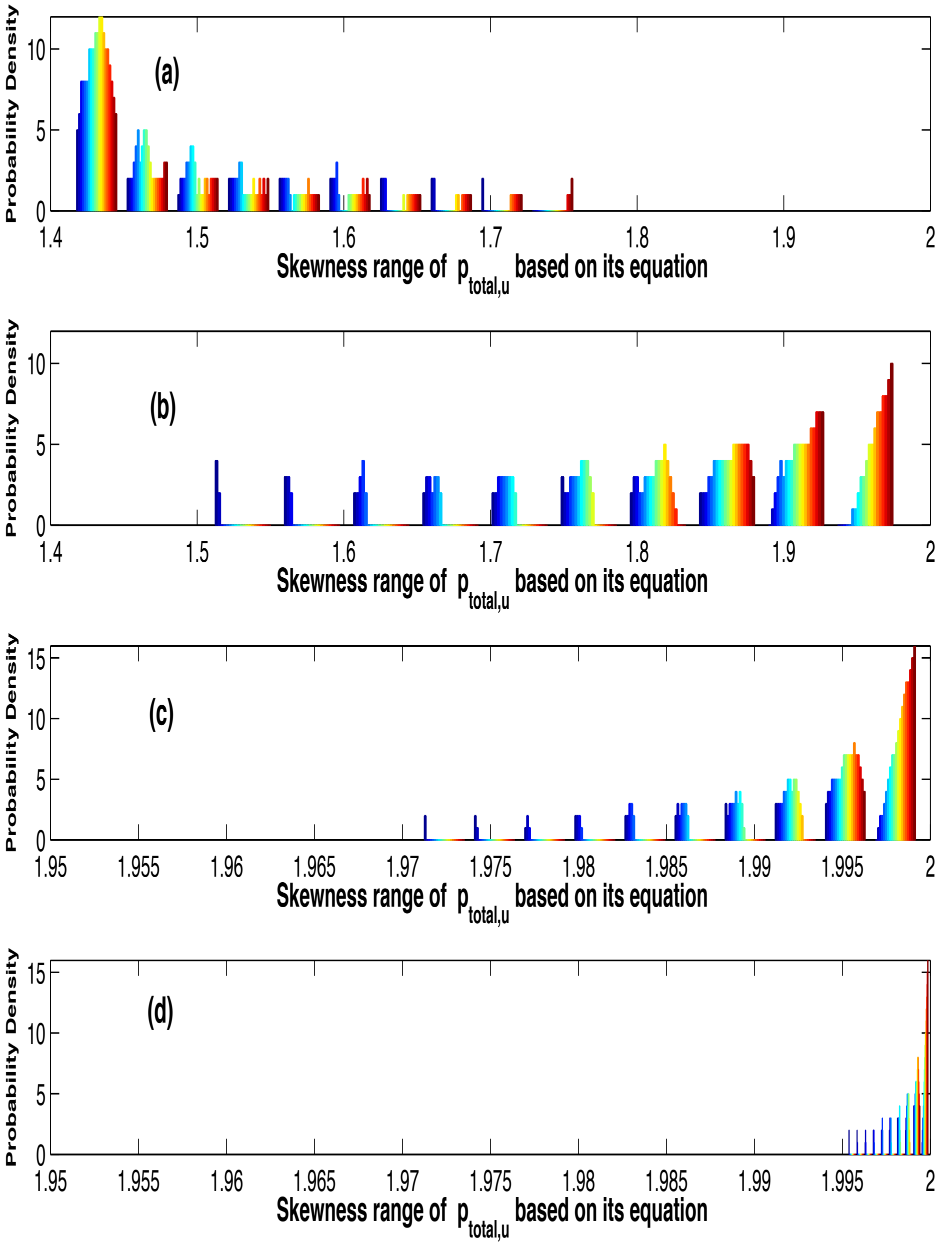

Figure 4.4: Skewness Range of $p_{total,u}$ Based on Expression (4.17) for Different Distance Ratios

(a) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=1

(b) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=2

(c) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=5

(d) Distance Ratio, $\frac{d_{1,u}}{d_{2,u}}$=8

test was analysed where each sensor node in the network is requested to decide whether or not it is an even-region node only based on its own environmental readings. Furthermore, a mathematical model for received signal power was presented featuring channel effects such as path-loss and fast-fading. Correlation between statistical attributes of received signal distribution at each node and the node's regional position with respect to two events were investigated in detail. Simulation results proved that each node can acknowledge its regional position based only on skewness range of its received power distribution. Based on the proposed approach, a $node_u$ is an event-region node only if the skewness of its total received power distribution satisfies the following rule: $2 - e \leq SK(p_{total,u}) \leq 2$.

Chapter 5

Conclusions and Future Research Directions

5.1 Conclusions

This work was motivated by the desire to achieve an optimal power allocation approach for OFDMA-based cooperative base stations by limiting interference, and also to obtain an approach for WSN system for classifying sensor nodes into two distinctive categories based only on the statistical attributes of their received signal.

Chapter 1 provided an introduction to WSNs and OFDMA-based systems, outlining their features, applications, challenges, and raising open research questions. Also a review of existing related literature on these subjects has been presented in Chapter 2 with emphasis on resource allocation in OFDMA-based systems and region/boundary detection in WSNs, underlining the shortcoming of existing research and the associated underlying assumptions.

Later in this thesis my findings and investigations on the followings has been discussed:

- Chapter 3 discusses the design of an optimal power allocation approach for OFDMA-based cooperative base stations by limiting interference. The objective of this approach is to maximise the sum rate of two interfering users, while limiting the received interference at each user, in an OFDMA-based system operating in downlink. To this end, three scenarios are presented: two sub-channels OFDMA-based system, N Sub-channel OFDMA-based system, and best channel conditions sub-channel selection. Furthermore, comparisons between achieved average spectral efficiency of the proposed interference power constraint resource allocation scheme as opposed to achieved average spectral efficiency by non-cooperative TDMA method is provided to prove that the proposed cooperative scheme outperforms non-cooperative TDMA approach.

- Chapter 4 discusses an approach for classifying sensor nodes into two distinctive categories based only on the statistical attributes of their received signal. For this purpose, a network of spatially distributed and wirelessly connected sensor nodes, monitoring an area of interest, is considered where this network is commissioned to detect two different phenomena occurring in distant parts of this area. To address this problem, a binary-hypothesis test is set in which each node is requested to decide whether or not it is an ever-region node based only on its own environmental readings. Thereafter, simulation results is provided to prove that each node can acknowledge its regional position based only on the statistical attributes of its own environmental readings. This is a promising approach because if only the nodes placed in the close-by region of each phenomena report back their readings to the BS, as opposed to transmitting entire readings from all the nodes, the required bandwidth reduces to be proportional to the size of that event-region only.

In conclusion, the main purpose of this thesis was to positively contribute to scientific knowledge, to clarify research aspects relating to OFDMA-based co-operative systems and WSN systems, and optimistically, to place question that may capture the interest of future researchers.

5.2 Future Research Directions

The research that has been undertaken for this thesis has successfully met the research aims and the time span proposed. However, in this section, areas of interest are identified which could be further investigated beyond the work presented in this thesis.

5.2.1 Extension of OFDMA-Based Cooperative System

The approach proposed in Chapter 3 can be extended to the case where there are more than two users on the edge of the neighbouring cells and also to a scenario in which the interference threshold level is adjusted according to the channel conditions.

5.2.2 Extension of Event Region Detection in Wireless Sensor Networks

The approach proposed in Chapter 4 can be extended to a scenario in which a network of spatially distributed and wirelessly connected sensor nodes are monitoring an area of interest where there are more than two different active phenomena, $j > 2$, occurring in distant parts of this area.

5.2.3 Lifetime Optimisation and Cognitive Radio in Wireless Sensor Networks

The main challenge in wireless networks originates from using resources efficiently such that the network throughput is maximised. On the other hand and as discussed in the beginning of this thesis, lifetime maximisation in non-rechargeable battery powered WSNs has been extensively studied in recent years. Energy consumption is a major limitation in such networks and there is a growing body of literature on this subject. A good survey of available technology appears in [29] and [55]. The scarcity of energy and bandwidth, the two fundamental resources for communications, imposes severe limitations on the development of communication networks in terms of capacity and performance. Among the new technologies, that have emerged recently in the effort to intelligently and efficiently utilise these constrained resources, are cognitive spectrum sharing. This promising technology is aiming at better utilisation of the available channel resources [56]. Cognitive radio prescribes the coexistence of licensed (or primary) and unlicensed (secondary or cognitive) radio nodes on the same bandwidth. While the first group is allowed to access the spectrum any time, the second seeks opportunities for transmission by exploiting the idle periods of primary nodes [57–60].

As mentioned earlier, one important perspective in WSNs field is to maximise the network lifetime where the network lifetime refers to the time interval from the deployment to the instant when the network is announced non-functional. Generally, the lifetime of a sensor node is inversely proportional to the average rate of information generated and relayed by it. On the other hand, the application performance of WSNs can be measured by the network throughput. A suggested research work for future, is to analyse these two problems jointly, with the objective to investigate the tradeoff between network lifetime maximisation and network throughput in WSNs. Although both have been topics of studies in recent years [61], [18], [62], few works considered them together and studied the tradeoff between them.

In the proposed model, a wireless network consisting of N primary and secondary nodes communicating their data with the BS is considered. The primary users access to the licensed band while a secondary group of nodes form an ad-hoc network and try to exploit the un-utilised channel resources either to communicate their own data packets to the BS or to relay for the primary users. According to the cognitive principle, the activity of the secondary link is required not to interfere with the performance of the primary. Therefore, it is assumed that the secondary link accesses the channel only when sensed idle [63]. The objective of this work is to maximise the network lifetime, defined in [64] and [65], while providing certain level of stable throughput.

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