AAU PhD Degree

Tentative Detailed Plan of Research

(11 Month's Study Plan)

Title

Spectrum Sensing Strategies for the Cognitive Cycle in Cognitive Radios

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Spectrum Sensing Strategies for the Cognitive Cycle in Cognitive Radios

Section 1: Summary /Abstract

General perception of spectrum scarcity due to fixed spectrum policies by the regulatory bodies motivated larger research effeorts in wireless communication [1]. It is found by extensive spectrum occupancy measurements all over the world [2] that this perception is wrong and the spectrum is not efficiently used. The concept of Cognitive Radio (CR) motivated by evolution of Software Defined Radio (SDR) [3] boosted the efforts in the direction of spectrum reuse by imparting cognitive capability to the radio.

The IEEE 802.11/HPERLAN standards for WLAN were the first to use the restricted cognitive capability in the form of Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). The WLAN or Wi-Fi devices operate on the ISM band. In spite of the use of cognitive capability and the 2009 amendment to 802.11 i.e. 802.11n, proposed 2400-2483.5 MHz band and 5150-5700 MHz band. Due to the scarcity in the bands used by access networks, in November, 2010, IEEE 802 group proposed an amendment in 802.11. IEEE 802.11af [4,5] is proposed to use TV white spaces for the access networks. It means, IEEE 802.11 devices have to employ the CR technology, in view to avoid interference to TV receivers and share the spectrum opportunistically.

This PhD project intends to investigate mainly on the spectrum sensing mechanisms along with conditions and considerations for its deployment in the WLAN access networks. This work also investigates deployment scenario selection for the important use cases of WLAN and physical modelling of the scenario to capture the major attributes of the real scenario.

In this regard this work primarily focuses on interference modelling for the considered scenario and deriving the statistics for accumulated interference to the Primary Users (PUs) due to multiple Secondary Users (SUs). The project undertakes the investigation of conditions and requirement for spectrum sensing in this scenario based on results of the interference statistics. Joint interference avoidance and distributed spectrum sensing is also considered for investigation in this study.

Section 2: Scientific Content

This description of the research project includes the background and relevance of the project problem to future wireless technology, the problem outline, state of the art and methodology based on the nature of the problem.

2.1: The Background for the Project Problem

In recent years, wireless communication has become very important mean of communication, firstly because of its flexibility in use and secondly due to its minimal post deployment maintenance costs vis-à-vis wired communication. However, electromagnetic spectrum is main enabling natural resource which is scarce due to fixed allocation policy prevalent in current scenario. The growing demand by diverse communication services has multiplied this spectrum scarcity problem. The freedom of using this scarce resource ubiquitously by any wireless device is the prime goal of current technological development in this area. However, the spectrum occupancy measurements carried out in USA, Europe and in India recently (by one of my colleagues) indicates that the perceived scarcity is due to dedicated partitioning of the spectrum bands and consequent allocation for a particular Radio Access Technology (RAT). Also it is due to operators trying to fit number of users in the same area at the same time and using the same frequencies.

Evolution of Cognitive Radio (CR) is viewed as a novel tool for improving the utilization of this precious natural resource. It is defined as an intelligent wireless communication system that is aware of its environment and configures itself by learning from radio environment. By this, ”it adapts to the statistical variations in the input stimuli with the primary objectives of providing ubiquitous and highly reliable communication along with efficient utilization of radio spectrum” [6]. The cognitive capability to the CR is imparted by execution of three cognitive tasks such as spectrum sensing, spectrum analysis and spectrum decision which is called as cognitive cycle.

The IEEE 802.22 Wireless Regional Areal Networks (WRAN) envisages incorporating this grand vision of CR, though limited cognitive capability is already incorporated in IEEE 802.11 by using Carrier Sense Multiple Access and Collison Avoidance (CSMA/CA). The FCC has identified TV band for CR deployment based upon the FCC task force report in 2002. IEEE 802.22 task group was formed to formulate standard for Wireless Rural Area Network which will opportunistically use TV band white spaces (Spectrum holes). The TV white space ruling in 2008 by FCC allows devices with combination of geo-location capability and sensing ability. Similarly IEEE 802.11 group has proposed to use TV white spaces extending it as standard IEEE 802.11af in 2010. In India, 700 MHz band is identified for CR usage and using military spectrum for CR deployment is discussed at many forums.

2.2: The State-of-the-art

The IEEE 802.22 working group [7] is developing a standard for use of CR in using TV white spaces and has described a framework for spectrum reuse [8]. This framework describes the inputs given and output expected from the spectrum sensing structure so that learning task in the cognitive cycle is achieved. This paper mentions that the framework does not mandate any particular sensing method. However, IEEE 802.11 group also proposes to formulate standards for use of CR to exploit TV white spaces by using spectrum sensing and location awareness [5].

The various approaches have been studied for interference constrained spectrum access that can be categorized under spectrum sharing using interference control and opportunistic spectrum access using spectrum sensing. The fundamental limits in spectrum-sharing in fading environments are investigated in [9]. Also the fundamental limits on spectrum sensing are studied in [10] where it is proved that single user sensing is inadequate to realize the spectrum sharing cognitive radio network. The different approaches for maximizing the total network capacity are studied such as graph theoretic approach [11, 12], game theoretic approach [13, 14]. The MIMO systems are exploited for spectrum capacity optimization in [15-19] which also discuss the information theoretic studies in this regard.

Energy detection is the most simple signal detection technique where the priori information of the signal format is not required. The detection of signal presence is done by statistical hypothesis testing. Some other forms such as sequential energy detection and energy detection using multiple antenna system are discussed in [20]. Energy detection with random amplitude signal is discussed in [21, 22] where the energy detection under random amplitudes of the signal received is discussed. Another sensing method used historically is matched filter detection which uses coherent detection method [23]. It is considered optimal since it maximizes the SNR but it requires complete information of the signal. Cyclostationary feature detector was first discussed for signal detection at receivers in [23] and it exploits the fact that all the telecommunication signals are modulated by sine wave carriers which result in Cyclostationary signals because its momentum exhibits periodicity. Wavelet based detection for wide band sensing is discussed in [20]. This method exploits the frequency resolution ability of the wavelet transform.

The other methods use cooperation in sensing from the other CR users or sensors. They are classified as multi-sensor methods. Extensive review of challenges in spectrum sensing is taken in [25]. Cooperative sensing methods uses techniques like eigenvalue based sensing, selective sensing and many other methods as proposed in [6, 20, and 24]. Game theoretic approach for cooperative sensing is suggested in [6]. The distributed spectrum sensing is considered in [26, 27].

2.2.1: Statement of the Project's Objectives

The project objective is to investigate the spectrum reuse challenges in Cognitive Radio networks deployed as Access Networks such as WLANs, which encompasses interference modeling, spectrum sensing in opportunistic spectrum sharing framework as parts of the cognitive cycle. It is expected to provide the novel solutions for spectrum sensing and interference avoidance problem as an outcome of this PhD research. The expected outcomes are descirbed in brief in the following.

- Interference modelling for ad-hoc random deployment of CRs and centrally coordinated CR deployment will be done. This includes computation of accumulated interference generated by the Cognitive Radio (CR) devices deployed on ad-hoc basis and/or with centralized coordination. The model should capture the realistic deployment scenario in campus wide ad-hoc deployment and the hotspots formed due to central coordination for spectrum access. The novel results of interference computations are expected to motivate further development of spectrum sharing and spectrum sensing mechanisms.

- A novel spectrum sensing mechanism in the form of algorithm for single band sensing and multiband sensing will be formulated. This will be done in context to coexisting primary and secondary devices. This algorithm is expected to maximize the probability of false alarm and minimize the probability of missed detection. In the first step, detection of primary signal at single CR user will be considered in Hypothesis Testing framework.
- Cooperative spectrum sensing by spatially distributed CR users will be investigated in optimization framework in the next step.
- The optimal distributes spectrum sensing algorithm will be formulated jointly with interference avoidance mechanism in the optimization framework.

2. 2.2: Problem Delineation

The Interference Problem: With reference to above discussion on the notion of spectral efficiency in context to Cognitive Radio where the metric used for computing the spectral efficiency is Bits/Sec/Hz /Unit Area, unlike in traditional radio where it is measured in bits/sec/Hz of the bandwidth. But according Shannon's limit more number of bits can be transmitted per Hz of the bandwidth requires more amount of energy.

This can be explained by Figure 1 in which we assume only one Primary User receiver (PU-Rx) located on the protection radius d_p. The area defined by d_{intmin} in the figure 1 is defined as the Direct Interference Zone (DIZ) for the PU-Rx where the decodability of received signal is not at all guaranteed and un-dotted circle represents the decodability radius (d_{dec}), where infinitesimal interference also can harm the decoding capability of the receiver at d_{dec}. If the SU transmitter (SU-Tx) is inside the d_{intmin} PU-Rx can be harmed by the interference from SU-Tx since there is all possiblity of SINR reducing below SNR threshold. Also The protection radius (d_p) is directly proportional to the amount of power transmitted by PU transmitter and fading conditions on the channel. This forms no-talk zone for SUs, which is directly dependent on the protection area.

These facts imply that the protection or censor radius for SU (d_{intmin}) is directly proportional to the d_p. Hence the secondary transmitter has limit on transmission when the primary spectrum is occupied. There is probability of transmission by SU when the PU is on the spectrum due to shadowing and hidden node effect on SU though it follows above limit. Also, the Sus which are outside the radius d_{intmin} and within the radius d_{intmax} defined here as 'Accumulative Interference Zone' (AIZ), cause accumulative interference to the PU-Rx.This accumulated interference due to multiple Sus affects the SINR level of the PU-Rx. The problem of secondary interference management gets multiplied when the SU nodes are not centrally coordinated.

Figure 1: Depiction of spectrum reuse problem

With this problem background, we can observe that the SU nodes located within DIZ interfere the PU-Rx and those located within the AIZ generate the accumulated interference. Hence we see two different strategies for opportunistic spectrum usage by the Sus located within the DIZ and that located within AIZ.

Opportunistic Spectrum Usage (OSU)

As discussed in the background, two approaches for spectrum access can be considered under above discussed situations viz, underlay and overlay approach. In this context, we define the following terms. The rationale behind defining these two confusing terms used alternatively in the literature of Cognitive Radio is to show that there are two clear cut approaches for achieving the spectrum reuse. Off-course, in real systems, they can be used in combination.

Opportunistic Spectrum Sharing (OSS): We define opportunistic spectrum sharing as a mechanism by which the Sus share the primary spectrum by detecting the spatio-temporal opportunity without violating the outage limit of the primary receiver. The outage occurs when SINR at PU-Rx is reduced below its detection threshold.

Opportunistic Spectrum Reuse (OSR): We define Opportunistic Spectrum Reuse as a mechanism in which an empty spectrum band is detected by secondary user (SU), using spectrum sensing techniques and used until the primary user (PU) returns for transmission on this band. The transmission is withdrawn by SU within the time limit prescribed by regulatory authorities.

2.3:

2.4: Research Methods

The research methodology for this project is described in the following paragraphs which elaborate on background study required, different approaches to realize the project, analysis of results, inferences based upon considered metrics and instantiation of outcomes.

2.4.1: Background Study

We consider spatio-temporal cluster modeling to capture the WLAN hotspot scenario mentioned in the problem definition. Hence study on Poisson Point Processes (PPP) is considered for interference modeling. Secondly, opportunistic spectrum sharing in multi-CR network is a constrained optimization problem. Hence, convex optimization theory is considered for study. Spectrum sensing in CR is fundamentally based on signal detection. The signal detection is used historically in communication systems at large. Detection techniques are based around knowledge of information theory, spectral theory and signal processing. The statistical methods are widely used for detection problem in the research work done so far. New approaches based on game theory are also suggested. The clarification of these mathematical concepts and their use for spectrum sensing will be included.

2.4.2: Concept Development

The concept is developed around the fundamental problem of interference avoidance in CRN and basic approaches proposed in literature. Also, the proposals by IEEE 802.22 and especially IEEE 802.11 (802.11af TV white space use) for use of cognition in WLAN motivate the problem definitions. The entire concept of scenario definition and underlying problem characterization is motivated by IEEE 802.11 proposal for TV white space usage.

2. 4.3: Key Methodological Approaches

To realize Opportunistic Spectrum Usage (OSU), above mentioned two approaches or their combination can be used in CR Network (CRN). The following three broad problems are envisioned.

Topology Considerations: The CR network topology and node distribution influence the spectrum access mechanisms applied for opportunistic spectrum usage. The distribution of nodes also affects the formation of interference field. We consider the WLAN hotspot scenario under fast fading and multipath channel conditions. Hence suitable spatial node distribution model to capture the ad-hoc deployment and formation of hotspots will be considered. The channel propagation characterization will be done by considering suitable propagation model.

Interference Modeling: As we observed in the problem description above that the direct interference and the aggregate interference influences the operation of CR in both underlay and overlay implementation i.e. OSS and OSR respectively. So the accurate modeling of interference from the interference field for a particular scenario is important. This depends upon the topology and the propagation environment considerations which must be realistic enough to capture the scenario. Interference Modeling is expected to specify the bounds on interference felt by the primary receivers. This decides the sensing threshold requirements for OSR approach and transmit-power constraint for OSS approach.

Single User Detection: A proper detection algorithm will be considered depending upon sensing time requirements, probability of missed detection and probability of false alarm constraints. The choice of algorithm will also consider the influence of cooperative sensing mechanism. The simulations will be carried out to investigate the performance of the algorithm in the above discussed deployment setting.

Optimal Cooperative Robust Sensing: Distributed sensing approach will be considered in Hypothesis Testing framework. The performance of the algorithm in the form of probability of missed detections and probability of false alarms will be tested by carrying out simulations for above discussed deployment setting.

Joint Interference Avoidance and Distributed Sensing: Interference avoidance will be considered for this research jointly with distributed spectrum sensing mechanism in optimization framework.

2. 4.4: Results Obtained and Analysis of Results

Interference statistics is derived and analytical simulations are carried out based on derived interference statistics for the WLAN scenario using Poisson distribution of secondary CR nodes. One PU-Rx located at protection radius as shown in *Fig-1* is considered. The detailed derivations and simulation results are presented in the Technical Report submitted to the supervisors.

Since we consider the WLAN with hotspots in the campus like scenario for our entire study, we consider the secondary node distribution by spatial clusters. The derivation of the statistics for the clusters and supporting numerical simulations is our further targeted work. This is in the view to derive the realistic limits for maximum and average power constraints to be applied in transmit-power control algorithms. The variation in primary transmit power does not affect the interferece caused to PU-Rx.

2.5: Significance and Applications

The spectrum sharing using cognition is important for a spectrum reuse mechanism ultimately leading to increased sum capacity of the wireless network. This study will help significantly in running a CR based spectrum access mechanism in WLANs.

2.5.1: Significance of the Outcome

This study will contribute in terms of algorithms for spectrum access in flexible spectrum sharing scenario in WLANs. This will also in designing the distributed cooperative spectrum sensing algorithms

2.5.2: Potential Applications

In this regards we address the problem of spectrum sensing for opportunistic spectrum sharing scenario in regards to Ad-hoc deployment and centrally coordinated deployment in WLAN access network is considered as potential application for this study.

2. 6: Time Schedule for PhD Research Project

The total time span of the research project (36 Months: 15 Nov 2009-14 Nov 2012) is divided in to three phases.

Phase-1: Research Accomplishment

Phase 1.1 (15 Nov 2009-14 Feb 2010): First three months of the PhD project is allocated for broader understanding and literature survey of cognitive radio and related areas of wireless communication. The broader study plan and time plan for the enitre period of the PhD project is prepared and submitted to PhD school. This phase also includes attending the course work scoring 7 ECTS points.

Phase 1.2 (15 Feb 2010-14 July 2010): This period includes clarifications on the information theoretic methods for wireless communication and mathematical methods required for the project such as statistical and algebraic methods. It also includes the attendance of the course work in India scoring 7 more ECTS points.

Phase 1.3 (15 July 2010-14 October 2010): Clarification on simulation methods applied for spectrum sensing and sharing and carrying out simulations of some of the well known detection algorithms. This phase was devoted also to detailed formulation of the entire PhD project and planning for focused work on interference modeling and different approaches related to spectrum access mechanism.

Phase 2: The Phase-2 includes the research accomplishments in the period 15 October 2010-14 October 2011. (i.e. work after 11 Months)

Phase 2.1 (15 October 2010-14 March 2011): This phase is used for problem formulation on interference modeling, deriving the statistics and inferring from the results. I theoretically determined the numbers of users that can be allowed in particular geographic area for given primary receivers SNR threshold. The simulations are carried out to compare the theoretical findings such as interference probability and aggregate interference due to secondary users to primary users. The Phase-2 includes the future plan for the period 15 May 2011-14 Nov 2012

Phase 2.2 (15 March 2011-14 June 2011): In this phase I accomplished the desired results on interference modeling for ad-hoc deployment and abstract of the paper was sent to 16th International OFDM workshop-2011 (InOwo'11) at Hamburg, Germany. In this phase the full paper was submitted to 16th International OFDM workshop-2011 (InOwo'11) and it was published subsequently. By the end of this phase the paper was accepted. Along with this, write of one chapter of thesis was completed.

Phase 2.3 (15 June 2011-14 October 2011): Write of one more draft chapter of the thesis is accomplished in this period. Furthermore, clarification on detection methods and algorithms and subsequent simulations of one of these algorithms for single user detection is accomplished.

Phase-3: This phase includes the period from 15 October 2011 to 14 November 2012. The 11 months plan broadly remains the same but present revision is more focused on problem formulation on spectrum sensing. The accomplished research results will be used in the future work on spectrum sensing. The revised plan includes stricter time plan for research deliverables so as to finish the project in three years of time frame.

Time Plan and Research Deliverables: The plan is subject to minor changes in terms of research accomplishments and time line. This does not include already delivered part of the two chapters of 25 pages.

Period	**Work Plan**	**Delivery Plan (no. Of pages of Thesis)**	**Delivery Date**	**Remarks**
15/10-01/11/2011	• Problem formulation for spectrum sensing mechanism. (Central idea: Distributed spectrum sensing of single band and multiband sectrum in Hypothesis Testing framework) • Discussion with supervisors on problem formulation • Improvements in first two chapters	Nil	NA	
01/11-14/12/2011	• Carrying out simulations on single user detection • Write of preliminary draft on spectrum sensing and spectrum sensing algorithms • Delivery of state of the art on single user detection algorithms	20 -25 pages	11/12/11	Part of Chapter 4
11/12/11-10/1/2012	• Studying the conditions for distributed spectrum sensing for TV band signals	20 pages	09/1/12	Part of Chapter

	and state of the art. • Write of second draft on Spectrum Sensing which includes technical issues and considerations for distributed spectrum sensing			4
11/1/2012-10/2/2012	• Simulations for comparing single user detection algorithms discussion results • Formulation of distributed spectrum sensing algorithm for adhoc deployment • Comments on performance of single user detection and distributed sensing mechanism with the help of simulation results	10 pages 10 pages 10 pages	09/2/12	Part of chapter 5
11/2-10/3/2012	• Comments on impact of central coordination in CR deployment scenario • Derivation of spectrum sensing mechanism considering the centrally coordinated deployment	10 pages 10 pages	09/3/12	Part of chapter 5
11/3-10/4/2012	• Simulations related to above sensing mechanism and discussions	08 pages	09/4/11	Part of chapter 5
11/4-10/5/2012	• Study of conditions for jointly considering the interference management/avoidance alongwith distributed sensig and state of the art	15	09/5/11	Part of chapter 6
11/5-10/6/2012	• Derivation of algorithm for joint interference avoidance and distributed spectrum sensing	15	09/6/11	Part of chapter 6
11/6-10/7/2012	• Simulations related to above topic and discussions	10	09/7/11	Part of chapter 6
11/7-10/8/2012	• Write of the chapter on distributed spectrum sensing mechanism	15	09/08/11	Part of chapter 6
11/8-10/9/2012	• Submission of the last chapter on Joint interference avoidance and spectrum sensing	15	10/9/11	Part of chapter 6
10/10/2012	• Submission of the first draft of the thesis		10/10/12	
1/11/2012	• Submission of the second draft of the thesis		1/11/12	
10/11/2012	• Submission of the final draft of the thesis		10/11/12	

Finally the thesis containing approximately 200 pages will be submitted by end of project

2.7: Outline of the PhD Thesis

Thesis will be a monograph and below is the draft of brief outline of the thesis.

Acknowledgement
Abstract
Table of Content
List of Figures
List of Tables

Section 3: Relationship between Supervisor and Student: The student –supervisor agreements can be summarized with following bullet points:

- The student and the supervisors are together responsible for time management in the project. The time plan for the PhD study should be reviewed every six months. From now onwards the time plan should be reviewed every three months.
- Telephone meetings (Skype) between the student and the AAU and Indian supervisors will take place at least every week. Meetings will take place once in two weeks with co-supervisor in India (to be clarified with Indian supervisor).
- The student should be able to get access to the lab equipment and the technical assistance at AAU and in India.
- Feedback regarding the progress and the quality of the work will be given during the meetings between the student and the supervisors.
- Most of the meetings will jointly be arranged by the student and the supervisors.
- Short minutes of the meetings with any of the supervisors will be prepared by the student and mailed to all the supervisors.
- The paper writing is on the basis of collaboration between the student and the supervisors.

Section 4: Plan for PhD Courses Adding up to 30 ECTS Credits

The courses mentioned in the following table are selected according to the 2010 schedule of the doctoral school at Aalborg University. Some of the courses will be taken in 2011 instead and some courses will be arranged in India by Aalborg University. Some courses (similar to some of the following courses) will be given by teachers from renowned institutions in India.

PhD Courses Completed and Planned

Courses	Place/ Organizer	ECTS	Joint or Project course	Status
Introduction To Internet Of Things	Nilee Prasad, Albena Mihovska, Zheng Hua Tan, Ole Brun Madsen,Aalborg	1	Project	Completed
Intellectual Property Rights	Lisbeth Tved Linde	2	Joint	Competed
Seminar for scientists-patenting and commercialization. 2/3 December 2009		1	Joint	Competed
Vehicular Communication 7th Dec.2009	Tatiana Kozlova Madsen and Hans-Peter Schwefel	3	Project	Competed
Air Interface Design for Future Wireless Systems – Towards Real 4G and Cognitive Radio	Prof. Ramjee Prasad, Prof. Frederiksen , Suvra Shekhar Das, Nicola Marchetti	4	Joint	Competed
Sensors and RFID Networks November 22-25,2010 , from AAU b Video conferencing	Assoc. Prof. Nilee Prasad.	3	Joint	Competed
Information---theoretic methods And tools for multiuser wireless Networks Ph.D. course	Petar Popovski	3	Project	Completed
MIMO Wireless Communications 11-13 May 2011	Assoc. Prof. Elisabeth de Carvalho	3	Project	Completed

The remaining course work of mandatory 7 ECTS is planned in third phase of the project.

Section 5: Dissemination of Knowledge and Findings

Dissemination of knowledge and findings is an important aspect of the research. I am focusing on publishing our research findings in important scientific journals and at conferences on cognitive radio, wireless communication and high speed signal processing. Also we aim at disseminating the accumulated knowledge on the topic of my research and related areas through lectures and seminars. Some relevant conferences and examples of the conferences which are scheduled in the near future are given in the following table. I plan to submit papers according to following priority list.

Sr. No	Probable Title of the paper	Publication Details
1	Interference Modeling for Cognitive Radio	16th International OFDM workshop-2011 (InOwo'11)August' 31 to September' 1, 2011, Hamburg, Germany **Accepted and Published)**
2	Distributed Sensing Mechanism for ad-hoc deployment of Cognitive Radio network	Globecom 2012 Anaheim, USA: 03-06 Dec 2012 **(**Paper to be submitted on 12 Feb 2012**)**

3	Distributed Sensing Mechanism for centrally coordinated deployment of Cognitive Radio network	IEEE PIMRC 2012 – The 23rd Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications IEEE PIMRC 09-12 Sep 2012**,** Sydeny, Austrialia (Paper submission 15 March 2012)
4	Spatial Modeling for computation of Interference in Cognitive Radio Network	EURASIP Journal on Wireless Communications and Networking – June 2012
5	Distributed Spectrum Sensing Mechanism for Cognitive Radio Network	Signal Procesing Letters August 2012
6	Joint Interference avidance and distributed spectrum sensing	Journal on Selected Areas in Communications October 2012

Section 6: Agreement on Immaterial Rights to Patents

The outcome of the research work will be registered for IPR and all the rights will be shared between the Aalborg University and the PhD student, following the standard procedures at AAU.

Section 7: External Collaborations

I am planning to work along with research group from Indian Institute of Technology, Bombay and eventually partly together with research laboratories of some multinational companies from India.

Section 8: Financing Budget to the PhD Project

Research facilities will be provided by AAU and financial support is provided by K.J. Educational Institutes, Pune, India.

Section 9: Bibliography

The following bibliography contains important and relevant references for consideration.

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