RESEARCH REPORT

VTT-R-08669-12

SMAS Project Final Report

Authors: Marja Matinmikko

Confidentiality: Public

Version 1.0/1.11.2012

Report's title	
SMAS Project Final Report	
Customer, contact person, address Academy of Finland	**Order reference**
Project name Spectrum Management for Future Wireless Systems	**Project number/Short name** 36009/SMAS (SA-SMAS2 in Vertti)
Author(s) Marja Matinmikko	**Pages** 9
Keywords Cognitive radio system, frequency channel, spectrum regulation	**Report identification code** VTT-R-08669-12

Summary

Spectrum Management for Future Wireless Systems (SMAS) project was a joint research project between VTT, Aalto University and University of Turku, funded by Academy of Finland. This report summarised VTT's research in the SMAS project. The SMAS project has developed advanced spectrum management techniques for future wireless networks to respond to the growing data rate and spectrum demand by facilitating spectrum sharing between different wireless systems. In particular, focus has been in cognitive radio system (CRS) capabilities for enabling spectrum sharing and improving spectrum use.

The project has carried out directional and distributed spectrum occupancy measurements to characterise the variations in the prevailing spectrum use in the spatial domain to identify spectrum opportunities for sharing. Knowledge of spectrum availability for sharing can be accomplished by several methods, including control channels, databases, and spectrum sensing techniques. In order to use proper methods in different situations, a novel band-specific approach has been developed where the selection of the method to obtain knowledge of spectrum availability is determined separately for each frequency band based on the deployment characteristics and regulatory requirements of the band. Moreover, a fuzzy rule-based decision making system is developed for the selection of spectrum sensing techniques. Channel assignment studies have been conducted to develop efficient means of exploiting the identified spectrum opportunities. The project has also carried out international cooperation on the spectrum management related aspects in several research and regulatory forums including e.g. COST Action IC0905 TERRA and International Telecommunication Union Radiocommunication sector (ITU-R).

Confidentiality	Public

Oulu 20.12.2012

Written by	**Reviewed by**	**Accepted by**
Marja Matinmikko, Senior Scientist	Kyösti Rautiola, Technology Manager	Jussi Paakkari Vice President, ICT

VTT's contact address

Distribution (customer and VTT)

VTT

Preface

The Spectrum Management for Future Wireless Systems (SMAS) project was conducted at VTT's Communication Platforms knowledge center in Oulu, Finland, in 2010-2012. The project was a cooperation project between VTT, Aalto University and University of Turku. The project was funded by Academy of Finland (decision number 134624). This report summarizes VTT's research in the project.

The SMAS project consortium was led by Prof. Jyri Hämäläinen from Aalto University. The project participants at VTT were Marja Matinmikko (project manager), Dr Tapio Rauma, and Marko Höyhtyä. The project work was supervised by Research Professor Aarne Mämmelä. VTT steering group consisted of the following participants: Aarne Mämmelä, Pertti Järvensivu/Markku Kiviranta and Marja Matinmikko as secretary.

The contributions from the project participants are gratefully acknowledged: Tapio Rauma, Marko Höyhtyä, and Res. Prof. Aarne Mämmelä from VTT, Prof. Jyri Hämäläinen, Prof. Olav Tirkkonen, Alexis Dowhuszko and Beneyam Berehnau Haile from Aalto University, Jussi Poikonen, Tero Hurnanen and Jari Tissari from University of Turku.

Oulu 20.12.2012

Marja Matinmikko

Contents

1. Introduction

Wireless communications has experienced strong growth during the past decades. The demand for mobile services keeps increasing towards the year 2020 which will result in increasing spectrum demand. While new spectrum was made available for the mobile service at the World Radiocommunication Conference in 2007 (WRC-07) by the International Telecommunication Union Radiocommunication sector (ITU-R), the requirements for new spectrum remain higher than what has been made available. Future wireless networks will need to find new ways of exploiting the scarce spectrum resource in order to meet the growing demand.

The emerging concept of cognitive radio systems (CRS) has been recognised as a potential tool for future wireless networks to get access to new spectrum resources by sharing spectrum with other systems. A CRS includes capabilities to obtain knowledge of system internal and external state, dynamically and autonomously adjust its operations accordingly, and learn from the results. Future CRSs can enhance spectrum sharing by exploiting temporarily and locally available spectrum while guaranteeing that primary systems remain free from harmful interference.

The SMAS project was established to develop new spectrum management approaches for future wireless networks to respond to the growing data rate and spectrum demand. The SMAS project was a cooperation project between VTT, Aalto University and University of Turku in 2010-2012. This report summarized VTT's part of the research project.

2. Goal

The overall goals of the SMAS project were the following:

- to improve the spectrum utilization to accommodate the future wireless systems,
- to study how resource management requirements will change when frequencies are liberated, and what algorithmic methods are attractive to use to fulfil the requirements,
- to evaluate the theoretical capacity of wireless networks in order to quantify how much can be gained in theory by utilizing spectrum sharing.

VTT's research has focused on the development of techniques for future wireless networks to cope with the growing data rate demand resulting in higher spectrum demand. The main idea behind VTT's research work was the following hypothesis:

- Future spectrum sharing networks call for compromise centric resource management that is accomplished by using intelligent decision making methods or their hybrid solutions.

VTT's research work was divided into three tasks:

- Task 1 (2010): Identification of spectrum management approaches
    - Identification of factors influencing efficient spectrum sharing, e.g. strategies for network use, and roles of different actors. Existing spectrum management approaches evaluated against new ideas emerging from the work. Publication work started.

- Task 2 (2011): Framework for optimal resource use
    - Criteria for optimal resource use in heterogeneous spectrum sharing networks. Theoretical investigation and modelling of alternative solutions for spectrum sharing policies and strategies. Publication work focuses on journal papers.

- Task 3 (2012): Advanced resource management techniques
  - Development of intelligent decision making methods for spectrum sharing. Simulation and performance evaluation of the developed methods. Writing of publications and PhD thesis finished.

3. Description

Spectrum management is a key functionality in the future wireless systems to accommodate the growing user demand with limited spectrum availabilities. Techniques for implementing more liberalized spectrum access are currently under discussion in the international spectrum regulatory bodies but the individual techniques are still unsolved. This project has developed techniques for spectrum sharing between wireless systems with a focus on three aspects:

1) Status of current spectrum use and influence of spatial dimension on the spectrum use
2) Selection among different methods to obtain knowledge of the availability of spectrum for sharing between different systems
3) Channel assignment methods to exploit spectrum opportunities.

The results are discussed in more detail in Chapter 6.

4. Limitations

The spectrum occupancy measurement studies are dependent on the threshold setting in the measurements. This work did not treat the threshold setting thoroughly but only set the thresholds empirically.

The band-specific approach for the selection of methods to obtain knowledge of spectrum availability is preliminary and considers the frequency bands at a general level. In practice, the situation of the spectrum use is more complicated and it can vary between different countries. Thus, the actual situation and the resulting band-specific approach are much more complex in reality.

The work on the selection of the spectrum sensing techniques was preliminary with the major aim of opening up a new research direction instead of providing a comprehensive solution to the problem. The work identified critical factors that influence the selection of the spectrum sensing technique and other factors could also be taken into account. The decision-making method presented relied on a number of assumptions to characterise the general classes of spectrum sensing methods.

The channel assignment studies have assumed that all information required for the decision making algorithm is available. In reality, the availability of information in practical settings is difficult to achieve and requires a large amount of control data exchange which may become impractical.

5. Methods

Research methods included literature reviews, measurements, simulations and active participation in international forums related to spectrum sharing.

6. Results

The project's results are documented in one doctoral dissertation [1], four journal papers [2]-[5], and nine conference papers [6]-[14]. In addition, two journal paper manuscripts ([15] and [16]) have been prepared and are currently in review process in journals. The results are summarized in the following.

6.1 Spatial dimension

The project has carried out directional and distributed spectrum occupancy measurements to characterise the variations in the prevailing spectrum use in the spatial domain in [5], [8] and [9]. Big variations in the spectrum occupancy were observed depending on the measurement location and direction in the same office area indicating that there are local and temporal spectrum opportunities that are being wasted in the current wireless systems. This is the first study to show that the spectrum occupancy can vary significantly depending on the measurement location even in the same office area at the same time.

In addition, the influence of the spatial dimension has been considered by studying the maximum number of users that can be allocated in the same frequency band when using beamforming in [14].

6.2 Selection of methods to obtain knowledge of spectrum availability

The project has developed decision making methods to improve the spectrum utilization in future wireless systems. Knowledge of spectrum availability for CRSs can be accomplished by several methods, including control channels, databases, and spectrum sensing techniques, which all have different capabilities, requirements and performances. In order to use proper methods in different situations, a novel band-specific approach has been developed in [9], [11] and [15], where the selection of the method to obtain knowledge of spectrum availability is determined separately for each frequency band based on the deployment characteristics and regulatory requirements of the specific band.

Moreover, a novel rule-based decision-making system with a learning mechanism is developed for the selection between different spectrum sensing techniques in [9], [11] and [15]. The developed method selects the most suitable spectrum sensing technique in a given situation to meet the requirements set by the spectrum regulator. This is the first work in the research literature to consider this problem.

Spectrum sensing as a specific technique to obtain knowledge of spectrum availability was studied in [13] by evaluating the performance of Welch's periodogram method. The achievable throughput that could be obtained when spectrum sensing is used to detect spectrum opportunities has been evaluated in [12]. Moreover, methods for power and subcarrier allocation are studied in [4].

6.3 Channel assignment

In order to exploit the available spectrum resources and assign the available frequency channels to the different users, the project has developed centralised and distributed channel assignment methods in [2], [3], [6], and [7]. Intelligent channel selection methods have been developed to improve spectrum use by exploiting the statistics of channel use in order to focus on the most promising spectrum channels in [7]. The channel assignment problem has been addressed in [2] by taking into account energy efficiency. Centralised and distributed channel assignment techniques have been developed in [3] and [6] using a heuristic Harmony Search algorithm.

6.4 International cooperation

The project has carried out international cooperation on the spectrum management related aspects in several research and regulatory forums. The project has participated actively in COST Action IC0905 TERRA on techno-economical and regulatory aspects of cognitive radio systems, where M. Matinmikko is Management Committee member and vice-chair of Working Group (WG 2) on CR/SDR coexistence studies. COST TERRA is developing a concept for spectrum sharing which summarized in [16].

Active participation in international spectrum regulation at International Telecommunication Union Radiocommunication sector (ITU-R) where M. Matinmikko acts as the chairman of CRS studies at the ITU-R Working Party 5A (ITU-R WP5A). Several presentations on future liberalized spectrum access using CRS techniques have been given to international spectrum regulators. Several invited keynote presentations have been held at international conferences (Mobilight 2010, CrownCom 2012)

International research cooperation has been carried out with Dr Javier Del Ser from TECNALIA Telecom, Spain, including several joint publications [2], [3], [4], [6], [9], [11] and [15].

7. Validation of results

The developed concepts have been verified by developing simulation models for the algorithms. Simulation studies have been conducted to evaluate the performances of the developed algorithms.

8. Conclusions

Future mobile communication networks will face serious challenges in the next decade due to ever growing numbers of subscriptions as well as the growing data rate requirements. The current development will inevitably lead to increasing spectrum requirements for mobile communication systems. Spectrum sharing using cognitive radio system capabilities can offer new spectrum opportunities for mobile communication systems. The presented results can be used in the development of future mobile communication systems enhanced with CRS capabilities to respond to the growing data rate and spectrum demand.

Future work in spectrum occupancy measurement studies could be done to study the availability and suitability of the spectrum opportunities for the operations of specific systems with CRS capabilities in specific frequency bands. In fact, distributed spectrum occupancy measurement studies could be done in the future for this purpose to capture the spectrum occupancy in a given area with several measurement devices and compare the measurements with the knowledge of the specific systems in the specific area and spectrum band. This information could be used to identify spectrum bands that are potential for sharing.

When it comes to the band specific approach for the selection of methods to obtain knowledge of spectrum availability, the major topic for future work is the more detailed study of the potential bands for CRS operations, derivation of the requirements for the protection of the primary users in the specific spectrum band, and the development of methods of obtaining accurate knowledge of spectrum availability in these bands.

Future work on channel assignment techniques could consider the amount of control information needed for the decision making in centralised and distributed approaches. Development of methods to efficiently distribute the required control information and to reduce the amount of control information would be an important topic to consider for practical applications.

Finally, the inclusion of learning techniques into the future wireless systems with CRS capabilities deserves further attention.

9. Summary

The SMAS project has developed advanced spectrum management techniques for future wireless networks to respond to the growing data rate and spectrum demand by facilitating spectrum sharing between different wireless systems. In particular, focus has been in cognitive radio system (CRS) capabilities for enabling spectrum sharing and improving spectrum utilization in future wireless systems.

The project has carried out directional and distributed spectrum occupancy measurements to characterise the variations in the prevailing spectrum use in the spatial domain to identify spectrum opportunities for sharing. Knowledge of spectrum availability for sharing can be accomplished by several methods, including control channels, databases, and spectrum sensing techniques. In order to use proper methods in different situations, a novel band-specific approach has been developed where the selection of the method to obtain knowledge of spectrum availability is determined separately for each frequency band based on the deployment characteristics and regulatory requirements of the band. Moreover, a fuzzy rule-based decision making system is developed for the selection of spectrum sensing techniques. Channel assignment studies have been conducted to develop efficient means of exploiting the identified spectrum opportunities. The project has also carried out international cooperation on the spectrum management related aspects in several research and regulatory forums including e.g. COST TERRA and ITU-R.

References

[1] Matinmikko, M. 2012. Spectrum sharing using cognitive radio system capabilities. Methods to obtain and exploit knowledge of spectrum availability. VTT Science 20. http://www.vtt.fi/inf/pdf/science/2012/S20.pdf

[2] Chen, T., Matinmikko, M. Del Ser, J. & Zhang, J. 2012. Energy efficient spectrum access in cognitive wireless access networks. Journal of Green Engineering, Vol. 2, No. 4, pp. 305-328.

[3] Del Ser, J., Matinmikko, M., Gil-López, S. & Mustonen, M. 2012. Centralized and distributed spectrum channel assignment in cognitive wireless networks: A Harmony Search approach. Applied Soft Computing, Vol. 12, No. 2, pp. 921-930.

[4] Del Ser, J., Bilbao, M. N., Gil-Lopez, S., Matinmikko, M. and Salcedo-Sanz S. 2011. Iterative power and subcarrier allocation in rate-constrained OFDMA downlink systems based on Harmony Search heuristics. Engineering Applications of Artificial Intelligence, Vol. 24, No. 5, August 2011, pp. 748–756.

[5] Matinmikko, M., Mustonen, M., Höyhtyä, M., Rauma, T., Sarvanko, H. & Mämmelä, A. Directional and cooperative spectrum occupancy measurements in the 2.4 GHz ISM band. Journal paper to appear in International Journal of Autonomous and Adaptive Communications Systems.

[6] Del Ser, J., Matinmikko, M., Gil-López, S. & Mustonen, M. 2010. A novel harmony search based spectrum allocation technique for cognitive radio networks. Proceedings of 2010 7th International Symposium on Wireless Communication Systems (ISWCS). York, U.K., 19-22 September 2010. Pp. 233-237.

[7] Höyhtyä, M., Sarvanko, H., Matinmikko, M. & Mämmelä, A. 2011. Autocorrelation-based traffic pattern classification for cognitive radios. Proceedings of IEEE VTC Fall 2011 conference, San Fransisco, September 2011.

[8] Matinmikko, M., Mustonen, M., Höyhtyä, M., Rauma, T., Sarvanko, H. & Mämmelä, A. 2010. Distributed and directional spectrum occupancy measurements in the 2.4 GHz ISM band. Proceedings of 2010 7th International Symposium on Wireless Communication Systems (ISWCS). York, U.K., 19-22 September 2010. Pp. 976-980.

[9] Matinmikko, M., Mustonen, M., Höyhtyä, M., Rauma, T., Sarvanko, H. & Mämmelä, A. 2010. Cooperative spectrum occupancy measurements in the 2.4 GHz ISM band. Proceedings of 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL). Rome, Italy, 7-10 November 2010. Pp. 1-5. ISBN: 978-1-4244-8131-6.

[10]Matinmikko, M., Mustonen, M., Rauma, T., & Del Ser, J. 2011. Architecture and approach for obtaining spectrum availability information. Proceedings of IEEE 73rd Vehicular Technology Conference (VTC Spring). Budapest, Hungary, 15-18 May 2011. Pp.1-5.

[11]Matinmikko, M., Rauma, T., Mustonen, M. & Del Ser, J. 2011. Decision-making system for obtaining spectrum availability information in opportunistic networks. Proceedings of 4th International Conference on Cognitive Radio and Advanced Spectrum Management (CogART). Barcelona, Spain, 26-29 October 2011. Pp. 1-6.

[12]Mustonen, M. & Matinmikko, M. 2011. Achievable throughput using cognitive principles on a frequency band with WWW traffic. Proceedings of 4th International Conference on Cognitive Radio and Advanced Spectrum Management (CogART). Barcelona, Spain, 26-29 October 2011. Pp. 1-6.

[13]Harjula, I., Hekkala, A., Matinmikko, M. & Mustonen M. 2011. Performance Evaluation of Spectrum Sensing Using Welch Periodogram in OFDM Systems. Proceedings of VTC 2011 Spring, Budapest, Hungary, 15-18 May, 2011.

[14]Sarvanko, H., Höyhtyä, M., Matinmikko, M. & Mämmelä A. 2011. Exploiting spatial dimension in cognitive radios and networks. Proceedings of 6th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), Osaka, Japan, May 2011.

[15]Matinmikko, M., Del Ser, J., Rauma, T. & Mustonen, M. Fuzzy-logic based framework for spectrum availability assessment in cognitive radio systems. Journal paper manuscript submitted to IEEE Journal on Selected Areas in Communications.

[16]Holland, O., Matinmikko, M., Nolan, K., De Nardis, L., Velez, F., Minervini, L., Medeisis, A., Sydor, J., Anker, P. & Aghvami, H. Pluralistic Licensing: The Core Concept and its Application to Next Generation Networks. Submitted to IEEE Wireless Communications Magazine.