
Contents

Acknowledgements	vii
Abstract	ix
List of Figures	xvii
List of Tables	xx
1 Introduction	1
1.1 Motivation	1
1.2 Objectives and Methodology	2
1.3 Organization of the thesis	3
2 Smartphone-based CrowdSensing: Existing Solutions	5
2.1 The CrowdSensing concept	5
2.2 Reference Architecture for Mobile CrowdSensing	9
2.3 Analysis of existing CrowdSensing proposals	20
2.4 Open research issues	43
2.5 Summary	43
3 Environmental Pollution: an Overview	45
3.1 Introduction	45
3.2 Pollution measurement	47
3.3 Studies addressing air pollution	51
3.4 Studies addressing noise pollution	54
3.5 Summary	58
4 Ecosensor: a mobile sensing architecture to monitor air quality	59

CONTENTS

4.1	Mobile sensing architecture overview	60
4.2	Monitoring Process	62
4.3	Finding the optimal measurement strategy	71
4.4	Validation of the proposed approach	76
4.5	Summary	79
5	GRC-Sensing: An Architecture to Measure Acoustic Pollution Based on CrowdSensing	81
5.1	Crowdsensing Architecture Overview	82
5.2	Summary	90
6	Accurate Ambient Noise Assessment Using Smartphones	91
6.1	Measuring Noise Level	92
6.2	Noise Calculation Algorithms	93
6.3	Calibration Procedure	95
6.4	Experimental Results	97
6.5	Validation in Real Outdoor Environments	109
6.6	Summary	113
7	Determining the Right Time to Obtain Noise Samples	115
7.1	Classification Techniques	116
7.2	Task sequencing optimization	120
7.3	Summary	127
8	Validation of the Proposed Architecture	129
8.1	Evaluation of our proposal in an isolated shopping area	130
8.2	Evaluation of our proposal in an urban area	130
8.3	Summary	134
9	Conclusions, Publications and Future Work	135
9.1	Publications	137
9.2	Future work	141
I	Appendices and References	143
A	Acronyms	145
	Bibliography	151

List of Figures

2.1	Generic structure of crowdsensing solutions.	6
2.2	Number of Crowdsensing-related proposals in the past 5 years.	9
2.3	Proposed Mobile CrowdSensing architecture.	10
2.4	Mobile Sensing Client (MSC) Components.	12
2.5	Cloud Data Collection Server Components.	17
3.1	Examples of health problems caused by environmental pollution (poor air quality and noise).	46
3.2	Example of an air monitoring station, and the location of the 5 stations available in Valencia, Spain.	47
3.3	Relationship between Air Quality and health.	48
3.4	Different types of Air Pollution sensors.	49
3.5	Different types of Sound Level Meter.	50
3.6	Typical Sound Levels (dBA).	51
3.7	Available apps for air measurement. (a) OzoneMap.; (b) BeijingAir.; (c) Caliope.	53
3.8	Available apps for noise measurement. (a) OpenNoise.; (b) Noise Capture.; (c) Ambicity.	56
4.1	Overview of the proposed mobile sensing architecture including the main hardware components and the technologies used.	61
4.2	Android-based application deployed monitoring screen (back) and path of a monitoring session (front).	63
4.3	Example of the cloud application web page showing some monitoring sessions, and the analysis output for two air pollutants.	64
4.4	Monitoring process overview showing the different tasks associated to each step in the process.	65

LIST OF FIGURES

4.5	Relationship between captured data and filtered data (left), and relationship between captured data variation and the filtered data variation (right)	66
4.6	Ozone evolution in June (left) and throughout the year (right)	68
4.7	Example of an ozone distribution heatmap for the Universitat Politècnica de València (UPV) using the proposed architecture.	70
4.8	Example of a semivariogram showing a Gaussian distribution. It shows the different parameters related with the interpolation techniques (Nugget, Sill and Range).	70
4.9	Analysis of the variability of mobile sensor readings: static vs. mobile sensor.	72
4.10	Analysis of the variability of mobile sensing for different sensor orientations.	73
4.11	Analysis of the output similarity with respect to reference sampling period (5 s)	74
4.12	Heatmaps for the ozone distribution using different sampling periods (5, 20, and 80 seconds)	75
4.13	Analysis of the similarity with respect to the reference trace (100% of the data used)	76
4.14	Heatmaps for the ozone distribution using different fraction of the original trace (100%, 72%, and 42%)	77
4.15	Comparison between captured data and typical values for the day/time of the year.	78
4.16	Ozone levels in the target region using infrastructure data.	78
4.17	Ozone level in the target region using mobile sensing.	79
5.1	General architecture for noise assessment based on crowdsensing.	83
5.2	Proposed crowdsensing architecture for mobile noise analysis.	84
5.3	Format of a JSON data message.	87
5.4	GRCsensing Web-based application.	88
6.1	Noise calibration using professional devices. Location: reverberant acoustic chamber, at the Universitat Politècnica de València.	96
6.2	Sampling rate analysis. (a) Algorithm #1; (b) Algorithm #2; (c) Algorithm #3.	98
6.3	Block size analysis. (a) Algorithm #1.; (b) Algorithm #2.; (c) Algorithm #3.	100
6.4	Sampling rate analysis when fixing the block size. (a) Algorithm #1; (b) Algorithm #3.	101
6.5	Smartphone models used for testing. From left to right: BQ Aquaris, Samsung J5, Samsung S4 and Samsung S7 Edge.	103

List of Figures

6.6	Estimation accuracy for the different smartphone models with and without linear regression. (a) Algorithm #1: default sampling; (b) Algorithm #1: values adjusted using linear regression; (c) Algorithm #1: estimation error.	104
6.7	Smartphones of a same model used for testing.	105
6.8	Estimation error analysis when using similar smartphones. (a) Before regression; (b) after regression; (c) estimation error.	106
6.9	Sampling period analysis. (a) S7 edge; (b) BQ Aquaris; (c) estimation error.	108
6.10	Analysis sampling S7 and Aquaris for 1 s.	109
6.11	Sampling period and error analysis when removing the first sample. (a) S7 Edge; (b) Aquaris; (c) error analysis.	110
6.12	Analysis for the mobile scenario.	111
6.13	Analysis of noise pollution for three outdoor scenarios. (a) Mobile scenario; (b) main avenue; (c) outdoor coffee shop.	112
7.1	Visualization of the automatically generated trees.	119
7.2	GPS analysis.	121
7.3	Processing time for the different tree elements.	122
7.4	Proposed resource-efficient decision tree.	125
7.5	Time and energy consumption corresponding to the different tree levels.	126
8.1	Task specification at the back-end server for noise distribution analysis at the Bonaire shopping mall.	130
8.2	Analysis of the environmental noise in a shopping mall. (a) Task specification at the back-end server; (b) Noise distribution of the shopping mall (Bonaire).	131
8.3	Specification of task at the back-end server for analysis noise distribution of the campus UPV.	132
8.4	Comparison of the distribution of environmental noise according to official data, and using our architecture.	133

List of Tables

2.1	Crowdsensing surveys.	8
2.2	Classification of the different crowdsensing proposals technologies according to the proposed architecture.	24
2.3	Classification of the different crowdsensing proposals according to the proposed client architecture.	30
2.4	Classification of the different crowdsensing proposal according to the proposed server architecture.	34
2.5	Classification of the different data transmission solutions according to the proposed architecture.	40
3.1	Characteristics of crowdsensing noise pollutions proposals.	57
4.1	Relationship between sensor readings and monitoring station readings.	67
4.2	Statistical summary of the sensor position analysis.	71
4.3	Statistical summary of the time sampling analysis.	73
4.4	Statistical summary of the spatial sampling analysis.	76
5.1	Size of the message with different selection areas and captured noise samples.	89
6.1	Estimation error and computational overhead achieved with the different algorithms (best overall configurations).	102
6.2	Sampling period analysis (when removing the first sample).	109
6.3	Error in the three outdoor scenarios.	113
7.1	Attribute candidate by categories.	117
7.2	Details of the training dataset.	123
7.3	Confusion matrix associated to phone status recognition.	123

List of Tables

7.4	Energy consumption estimation for each leaf of the tree.	124
7.5	Estimation of computational requirements and energy consumption for the different decision trees.	127