AN INTEGRATED FRAMEWORK FOR ENERGY OPTIMIZATION OF WIRELESS SENSOR NODES

by

Sonali Chouhan

Electrical Engineering Department

Submitted

in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the

Indian Institute of Technology Delhi
October 2009

Certificate

This is to certify that the thesis titled **An Integrated Framework for Energy Optimization of Wireless Sensor Nodes** being submitted by **Sonali Chouhan** for the award of **Doctor of Philosophy** in **Electrical Engineering** is a record of bona-fide work carried out by her under our guidance and supervision at the **Electrical Engineering Department, Indian Institute of Technology Delhi**. The work presented in this thesis has not been submitted elsewhere, either in part or full, for the award of any other degree or diploma.

Ranjan Bose
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi 110 016

M. Balakrishnan
Professor
Department of Computer Science and Engineering
Indian Institute of Technology Delhi
New Delhi 110 016

Acknowledgments

Many people have helped me in the course of my research and any merit in it is in large measure due to them. First of all, I wish to express my profound gratitude to my supervisors Prof. Ranjan Bose and Prof. M Balakrishnan for their continued encouragement and invaluable suggestions during this work. I will always be thankful for their wisdom, knowledge, and deep concern for me. It has been an honor to work with them.

I wish to thank Prof. Rakesh K. Patney, Prof. Shankar Prakriya, Prof. Shivdatt Joshi, Dr. Monika Aggarwal and Dr. Kolin Paul for their valuable feedback, suggestions and encouragement in all respect. I wish to extend sincere thanks to Prof. Anshul Kumar and Prof. A. N. Jha for their advice and encouragement.

I would like to thank my colleague Neeraj Goel for his feedback during our informal discussions and Lava Bhargava, Aryabratta Sahu, Anant Vishnoi, G Krishnaiah, BVN Silpa, Ayesha Choudhary, Smruti Padhy and all the other colleagues for their cooperation and support.

I would also like to thank the staff of Philips and FPGA laboratories, IIT Delhi, Mrs. Vandana Ahluwalia and Mr. S. D. Sharma for their help. They have opened their hearts and their doors, supplying me with resources I never could have found without them.

Finally, I want to thank my family. The patience, love, and encouragement from my husband Mahendra Singh Chouhan and our always positive and joyful daughter Mallika is a powerful source of inspiration and energy. A special thought is devoted to my parents for a never-ending support.

Sonali Chouhan

Abstract

Advances in VLSI technology has made very small sensor nodes possible. The sensor nodes broadly incorporate sensors, a processor, limited memory, and a radio. Wireless network of these sensor nodes form a Wireless Sensor Network (WSN). WSN is deployed for a wide variety of applications and includes both indoor and outdoor settings. Some example applications are landmine detection, monitoring volcano eruption activities, habitat monitoring, medical diagnosis, disaster management, fire monitoring, etc. In most of these applications the sensor nodes are battery driven. Battery driven sensor nodes are easy and fast to deploy but changing batteries frequently is neither convenient nor economical. Therefore, reducing energy consumption of a sensor node is essential.

This thesis is targeted towards reducing sensor node energy using system level techniques. In a sensor node, major energy contributors are the computation unit and the radio unit. We have proposed a methodology to explore the design space and to find energy efficient sensor node configuration based on the trade-off between the computation energy and the radio energy.

The required bit error rate (BER) is application dependent and could differ significantly. For example, acceptable BER is much lower in medical applications as compared to the environment monitoring applications. For achieving desired BER, normally error correcting codes (ECCs) are used. For achieving a certain BER, the signal to noise ratio (SNR) required for transmitting data with ECC is less as com-

pared to sending data uncoded. This saving in signal power is known as the coding gain. The energy overheads of ECC relate to energy spent in encoding and decoding of data and energy spent in transmission of "redundant" bits. We can trade-off these energy overheads against the energy gain due to the coding gain of ECC. With this trade-off in energy, a design space is created for selecting an appropriate ECC, which not only maintains BER, but may also reduce the energy consumption of the sensor node. For a desired BER, required SNR is also determined by the modulation scheme used. The energy consumptions due to ECC and modulation are interdependent. Therefore, our design space considers both ECC and modulation scheme. The energy consumption of a sensor node is a complex function of inter-node distance, desired BER, channel conditions, operating frequency, modulation schemes, and error correcting codes. This thesis presents a systematic methodology to explore such a design space and find an energy efficient sensor node configuration.

The proposed methodology takes into account the radio energy as well as the computation energy of a sensor node with various design space parameters. To compute the sensor node energy we have developed an energy model, that is used to explore the design space with various ECCs and modulation schemes. The design space created with previously mentioned application and deployment related parameters becomes very large. The sensor node energy analysis with respect to ECC and modulation parameters, i.e., error-correction capability, code word length, and modulation constellation size, reduces the design space significantly. This makes the exploration faster and gives an energy efficient ECC-modulation pair. Further, we have classified the inter-node distance in three categories: the short, the medium, and the large distance. We have formulated these distance ranges and their boundaries, and studied the trade-off among node energy components over these ranges. The proposed methodology has been validated by energy measurement of an off-the-shelf sensor node, Imote2, with and without ECC in different operating conditions.

The key contributions of the thesis are as follows.

- A system level framework has been developed to explore design space and to find an energy efficient node configuration. This design space is formed by taking the feasible range of values for a set of parameters that affect the node energy consumption.
- Developed a sensor node energy model that consists of three significant energy components of a sensor node; the circuit, the signal, and the computation energy.
- Explored the design space by taking application and deployment conditions into account. It has been shown that the node energy is a function of internode distance, desired BER, path loss exponent, modulation scheme, and ECC used.
- An analysis based on analytical models has been carried out for the sensor node energy with ECC and modulation parameters. It has been shown that for a given operating condition an energy efficient ECC-modulation pair can be obtained.
- We have proved that the sensor node energy is minimal for a particular error correcting capability and code word length of RS codes for a given operating condition. This helps in reducing design space significantly.
- Classified and formulated distance ranges based on identifying significant contributions of signal, circuit, and computation energy to the node energy consumption with distance.
- Notion of crossover distance and threshold distance from the perspective of energy dominance of key node energy components have been proposed.
- Validated our methodology by deploying on an off-the-shelf sensor node, namely, Imote2.

Contents

List of Tables vii

List of Figures ix

1 Introduction 1

1.1 Motivation 1

1.2 Objective 3

1.3 Background 3

1.3.1 Wireless Sensor Node and Network 3

1.3.2 Energy Reduction in Wireless Sensor Network 6

1.3.3 Processor Energy Estimation 8

1.4 Review of Previous Work 10

1.5 Overview of the Work Done 13

1.6 Thesis Organization 13

2 Framework for Design Space Exploration 15

2.1 Introduction 15

2.2 Methodology 16

2.3 Exploration Framework 18

2.4 Sensor Node Energy Model 21

2.4.1 Radio Energy Model 21

2.4.2 Computation Energy Model 26
2.4.3 Node Energy 27
2.5 Summary 27

3 Exploring Low Energy Node Configurations with Application and Environment Parameters 29

3.1 Introduction 29
3.2 Experimental Setup 30
3.3 Significance of Energy Components 32
3.3.1 Computation–Radio-Energy Trade-off 32
3.4 Effect of WSN Deployment on the Sensor Node Energy 35
3.4.1 Distance 36
3.4.2 Energy Optimal ECC at Different Bit Error Rates 37
3.4.3 Path Loss Exponent (PLE) 38
3.5 Sensor Node Energy Variations with Modulation and ECC Parameters 41
3.5.1 Constellation Size 41
3.5.2 ECC Parameters 43
3.6 Qualitative Analysis 45
3.7 Summary 46

4 Exploring Low Energy Node Configurations with ECC and Modulation Options 49

4.1 Introduction 49
4.2 Crossover Distance 51
4.3 Effect of ECC and Modulation Parameters on Signal Energy 52
4.3.1 Signal Energy with Variation in t and b for Constant N 53
4.3.2 Signal Energy with Variation in Values of N and b while Keeping t Constant 56

4.4 Node Energy Variation with ECC and Modulation Parameters 58
4.5 Simulation Results 60
4.5.1 Crossover Distance 60
4.5.2 Node Energy Variations 63
4.5.3 Optimal Energy Configuration 63
4.6 Summary 64

5 Classifying Distance Ranges Based on Contribution of Energy Components 67

5.1 Introduction 67
5.2 Classification of Distance Ranges 68
5.3 The Short Distance Range Sensor Node Energy 70
5.3.1 MPSK Modulation 71
5.3.2 MQAM Modulation 74
5.3.3 MFSK Modulation 75
5.4 The Node Energy at the Medium Distance Range 76
5.5 The Threshold Distance and Sensor Node Energy at the Large Distance Range 80
5.6 Sensor Node Energy at Short, Medium, and Large Distances 85
5.7 Future Trends 86
5.8 Summary 88

6 Validation Using a Real Sensor Node 91

6.1 Introduction 91
6.2 Validation Framework 92
6.3 Implementation Issues 94
6.3.1 Limited Packet Length 94
6.3.2 Predefined Modulation Scheme 94

6.3.3 Limited Transmit Power Levels 95
6.3.4 Significant Computation Energy Consumption 95
6.4 Experimental Methodology 96
6.4.1 Energy Measurement 97
6.4.2 BER Measurement 98
6.5 Results 98
6.5.1 Radio Current and Energy Consumption 99
6.5.2 Computation Energy Optimization 101
6.5.3 Radio and Computation Energy with Various Hamming and RS Encoding 103
6.5.4 BER Measurement 104
6.5.5 Sensor Node Energy Consumption for a Constant BER 105
6.6 Summary 110

7 Conclusions **113**

7.1 Research Contributions 113
7.1.1 Methodology and Framework for Design Space Exploration . . 114
7.1.2 Energy Modeling of the Sensor Node 115
7.1.3 Exploring Low Energy Configurations with Application and Environment Parameters 115
7.1.4 Exploring Low Energy Configurations with ECC and Modulation Options 116
7.1.5 Classifying Distance Ranges Based on Contribution of Energy Components 118
7.1.6 Validation Using a Real Sensor Node 120
7.2 Future Research Directions 121
7.2.1 Framework Expansion for the Sensor Network 121
7.2.2 Low Power Solutions 122

Bibliography 123

A 135