Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department

CONVERGENCE of WIRELESS SENSOR NETWORKS and 4th G MOBILE

A Thesis
Submitted in partial fulfillment for the requirements
for the degree of Doctor of Philosophy in Communications Engineering
(Electronics and Communications Engineering)

Submitted by

Mehaseb Ahmed Mahmoud Mohamed

B.Sc. in Electrical Engineering
Electronics and Communications Engineering Dept.
Helwan University, 2004

M.Sc. in Electrical Engineering
Electronics and Communications Engineering Dept.
Helwan University, 2010

Supervised by

Prof. Hadia Mohamed Said El Hennawy

Electronics and Communications Engineering Dept.
Ain Shams University
Faculty of Engineering

Cairo 2018

Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department

Judgment Committee

Name: Mehaseb Ahmed Mahmoud Mohamed
Thesis: Convergence of wireless sensor networks and 4^{th} G mobile
Degree: Doctor of Philosophy in Communications Engineering

Name, Title and Affiliation	**Signature**
Prof. Hesham Mohamed Abdel Ghafar El Badawy Network planning Dept. National Telecommunication Institute (NTI)	……………
Prof. Abdel Halim Abdel Naby Zekry Electronics and Communications Engineering Dept. Faculty of Engineering, Ain Shams University	……………
Prof. Hadia Mohamed Said El Hennawy Electronics and Communications Engineering Dept. Faculty of Engineering, Ain Shams University	……………

Date: 10 May, 2018

Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department

Statement

This dissertation is submitted to Ain Shams University in partial fulfillment of the degree of Doctor of Philosophy in Communications Engineering (Electronics and Communications Engineering).

The work included in this thesis was carried out by the author at the department of Electronics and Communications Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis was submitted for a degree or qualifications at any other university or institution.

Name : Mehaseb Ahmed Mahmoud Mehaseb

Signature :

Date : 10 May, 2018

Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department

Curriculum Vitae

Name of the researcher	: Mehaseb Ahmed Mahmoud
Date of Birth	: 1 – 8 – 1982
Place of Birth	: Cairo
Nationality	: Egyptian
Last University Degree	: M.Sc. in Electrical Engineering (Electronics and Communications) Faculty of Engineering, Helwan University.
Certification Date	: July 2010

Name	: Mehaseb Ahmed Mahmoud
Signature	:
Date	: 10 May, 2018

Acknowledgements

In the name of God the Most Gracious, the Most Merciful, to Him we belong and all the praise and thanks are due. By only His will our efforts could ever be fruitful and our plans could ever be seen through. No matter how much knowledge we acquire, He remains the utmost knowing and before His name, none of the following deserving's may show.

My deep and sincere thanks, gratitude and respect are due to my academic supervisor and research mentor, Prof. Hadia El Hennawy and Prof. Hesham EL Badawy. No doubt, I would attribute the success of this PhD to their on-going guidance that was never limited to the highly professional academic and technical supervision. I must also acknowledge their persistent encouragement and inspiring enthusiasm to conduct the research.

On the personal side, special thanks and gratitude to my beloved parents for their continuous support and encouragement throughout my career, I would like also to express my appreciation and gratefulness to my beloved wife for her tireless support, understanding, patience, and countless sacrifices.

Publications

M. A. Mehaseb, Y. Gadallah and H. El-Hennawy, "WSN Application Traffic Characterization for Integration within the Internet of Things," *2013 IEEE 9th International Conference on Mobile Ad-hoc and Sensor Networks*, Dalian, 2013, pp. 318-323.

M. A. Mehaseb, Y. Gadallah, A. Elhamy and H. Elhennawy, "Classification of LTE Uplink Scheduling Techniques: An M2M Perspective," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1310-1335, Second quarter 2016.

M. A. Mehaseb, H. El-hennawy and H. El-Badawy "Predictive Delay Based Resources Allocation Algorithm for MTC in Disaster Area" *The International Congress of Telematics & Computing WITCOM 2017*, Cancún, Mexico, November 2017.

Abstract

The Internet of Things (IoT) can be considered the future of the Internet. IoT aims at providing an Internet connection to widely distributed devices with sensing or actuating capabilities. This would eventually lead to tightly integrating wireless sensor networks into the Internet that we are all familiar with nowadays. Wireless sensor networks (WSNs) can be found in many applications today. Examples are surveillance, forest fire detection and combating, healthcare etc. The data collected by WSN devices can be of interest to many users which could be residing far away from where these networks are actually installed. Since these networks may be installed remotely where access to Internet infrastructure may not be easily available, we need some access technology that can provide the link between the two worlds. LTE, due to its unique characteristics which include internet protocol (IP) compatibility and relative ease of deployment, can play an important role in the IoT.

LTE can be used to provide the needed Internet connectivity for WSNs. However, this integration process faces important challenges. One of the main challenges is that LTE is mainly designed for human to human communications such as voice calls, video streaming, online gaming, and social networking. On the other hand, due to the difference in the applications that are supported by WSNs, the traffic generated by these networks is completely different than the regular traffic that can normally be served by LTE (i.e. human to human traffic). Therefore, traffic modeling of WSNs is a crucial step towards finding a common ground for the integration between the two network types.

Machine to machine (M2M) communications is considered a subset of IoT. For this purpose, the 3GPP group is working to evolve LTE to support the requirement of M2M communications. Resulting from their efforts are the architectural model and the requirements of M2M communications over LTE-Advanced. Architecture, challenges and applications of machine to machine communications.

In this thesis, we aim to shed some light on the integration requirements between WSNs and LTE within the framework of the M2M. This is done by

- Studying different LTE scheduling and resource allocation techniques form M2M perspective. Hence, we categorize resource allocation into four categories; Power-efficient schedulers, Quality of Service-based (QoS) schedulers, Multi-hop-based schedulers and low complexity schedulers. This categorization is based on MTC requirements.
- Studying the traffic characteristics of a certain MTC application such as intrusion detection system and discussing the possibility of mapping traffic pattern that is generated from MTC system to what is normally expected by LTE networks. Studying traffic characteristics enables us to design a resource allocation algorithm that is capable to support M2M traffic.
- Design low complexity scheduling algorithm designed for MTC, by using Doubly Stochastic Approximation (DSA) method. The algorithm designed mainly in order to maximize the sum rate of the eNB and minimize the delay of MTC devices deployed in disaster area with delay critical applications.
- Design a radio resource division algorithm to divide the available resources between different eNBs deployed in disaster area where there is no LTE coverage, the algorithm divide resources between nodes taking into consideration the QoS requirements of MTC devices.
- Finally, we introduce the predictive resource allocation algorithm by using weighted least square error (WLSE) algorithm, where the resource allocation algorithm tries to predict the allocation parameters in order to decrease delay.

Keywords: Internet of Things; LTE Scheduling; Machine to Machine Communication; Machine Type Communication; Quality of Service; Resources allocation; Traffic Characterization.

Table of Contents

Acknowledgements i

Publications ii

Abstract........ iii

List of Symbols........ viii

List of Tables........ x

List of Figures........ xi

List of Acronyms........ xiii

Chapter One:........ 1

INTRODUCTION........ 1

1.1 Internet of Things and M2M communication 1

1.2 M2M Applications and Usage Models 1

1.3 M2M System Model 4

1.4 M2M and LTE Integration Challenges 7

1.5 Literature Review 10

1.6 Network model 11

1.6.1 System initialization........ 13

1.6.2 Radio Resource Management (RRM) proxy-eNB election........ 14

1.7 Problem Statement and Thesis Contributions 14

1.8 Thesis Organization 15

Chapter Two: 17

LTE Packet Scheduler 17

2.1 LTE Packet Scheduler Structure 17

2.2 Scheduling Parameters........ 20

2.2.1 Buffer Status Report (BSR) 21

2.2.2 Channel Quality information (CQI) 21

2.2.3 Signal to Interference Noise Ratio (SNIR)........ 22

2.2.4 Power headroom (PHR) 23

2.2.5 Hybrid ARQ........ 23

2.3 LTE Scheduling Aspects 23

2.4 Summary 24

Chapter Three: 25

LTE Schedulers Classification and Resources Allocation: M2M Perspective 25

3.1 Power-efficient Scheduling 25

3.1.1 Reducing the Number of Assigned PRBs 27

3.1.2 Increasing the Transmission Time 30

3.2 Quality of Service-based Scheduling 34

3.2.1 Throughput-based Scheduling Techniques 36

3.2.2 Delay-based Scheduling Techniques 39

3.3 Multi-hop-based Scheduling 43

3.3.1 Multi-hop Communications via LTE Relaying 45

3.3.2 Multi-hop via Device-to-Device (D2D) Communications 50

3.4 Complexity of Scheduling Algorithms 55

3.5 Summary 64

Chapter Four: 66

M2M Traffic Characterization for Integration over LTE 66

4.1 Introduction 66

4.2 MTC Traffic Models 67

4.3 Simulation and Results 69

4.4 Discussion and Conclusion 74

4.5 Summary 75

Chapter Five: 76

Low complexity M2M Scheduling using Doubly Stochastic Approximation76

5.1 Introduction 76

5.2 Optimization problem 76

5.3 Binary Integer Programming 78

5.3.1 Branch and bound 79

5.4 Doubly Stochastic Approximation for Resources allocation (DSA-RA) 80

5.4.1 Row optimization 81

5.4.2 Column optimization 82
5.4.3 Brikhoff's Theorem 83
5.4.4 MTC scheduling algorithm using DSA 84
5.5 Mathematical Analysis 86
5.5.1 Throughput analysis 90
5.5.2 Delay analysis 90
5.6 Performance Evaluation 91
5.7 Simulation Results 91
5.7.1 Throughput: 92
5.7.2 Fairness Index: 94
5.7.3 Computational complexity 95
5.7.1 Delay 96
5.8 Summary 99
Chapter Six: 100
Centralized QoS Aware Resource Division Algorithm for Disaster Area Network 100
6.1 Introduction 100
6.2 Optimization problem 101
6.3 Resources division algorithm using DSA 104
6.3.1 Resources Division Based on offered load 105
6.3.2 Resources Division Based on Delay 107
6.4 Simulation Results 109
6.5 Predictive resource division algorithms 113
6.6 Weighted Least Squares Estimation Algorithm (WLSE) 114
6.6.1 Performance evaluation of WLSE 115
6.7 Summary 120
Chapter Seven: 121
Conclusion and Future Work 121
References 124
Appendix A 138

List of Symbols

n_{proxy}	Number of proxy-eNBs
B	the available bandwidth (Hz), is the bandwidth of physical resource block
B_{PRB}	the bandwidth of physical resource block
$um_{i,j}$	Urgency metric of the device *i* attached to proxy-eNB *j*
$BSR_{i,j}$	The BSR of the device *i* attached to proxy-eNB *j*
A	Allocation vector
$r_{i,j}(t)$	the data rate of terminal *i* attached to proxy_eNB *j* in time slot t
$c_{i,j}$	the chunk of resources allocated to terminal *i* attached to proxy_eNB *j*
P_{max}	the maximum transmission power of the device
$P_{i,j}(c_{i,j}, t)$	the uplink transmit power of node *i* to the proxy_eNB *j*
PF	Priority factor
N_{PRB}	Number of available physical resource blocks
$N_{PRB,j}$	Number of resources assigned to proxy-eNB *j*
$M_{i,j,r}$	The metric of the device *i* attached to the proxy-eNB *j*, for the resource block *r*
ρ	the Path Loss compensation factor
$CQI_{i,j,r}$	The CQI of the device *i* attached to the proxy-eNB *j*, for the resource block *r*
$CQI_{,j,r}$	The median CQI value of devices attached to proxy-eNB *j*, for the resource block *r*
R_j	The total rate of the proxy-eNB *j*
π_n	the steady sate probability of state *n*
θ_k	the probability of using MCS *k*
T_{SR}	The scheduling request receiving time
T_{GRNAT}	The resources granting time
$d_{max}(i)$	The maximum delay budget of the device *i*
$WT_i(t)$	The average waiting time of the device *i* in the scheduling queue.

$CQI_{i,r}$	The average channel gain of PRB r of the device i.
$\overline{\mu}$	Average departure rate of the scheduler
W	The average waiting time spent in the queue by a device
N_q	The average number of devices initiate scheduling request
N_s	Average number of users selected by the TDS and scheduled by FDS in the next TTI
N_{a}	Total number of active devices at time "*t*"
$B(N_a)$	The number of bits transmitted in the TTI interval when n_a users are in the system
b	Size of data to be transmitted in bits
T_d	Average time spent in the system by a device, i.e. scheduling time delay
$\mu(N_a)$	Departure rate of the scheduler when N_a users are active in the system
α	Forgetting factor

List of Tables

TABLE 3-1 STANDARDIZED QCI CHARACTERISTICS [63] 35

TABLE 3-2 M-LWDF SCHEDULING ALGORITHM [66] 38

TABLE 3-3 RADIO RELAYING SCHEMES 47

TABLE 3-4 HUNGARIAN METHOD FOR OPTIMAL RESOURCE ASSIGNMENT 55

TABLE 3-5 (A) DETAILS OF THE FME, RME AND MADE SCHEDULING TECHNIQUES [131] 58

TABLE 3-6 SEARCH TREE-BASED ALGORITHM 60

TABLE 3-7 IRME SCHEDULING TECHNIQUE [132] 62

TABLE 4-1PARAMETERS USED TO OBTAIN SIMULATION 71

TABLE 5-1 BIP BRANCH AND BOUND ALGORITHM FOR RESOURCES ALLOCATION 79

TABLE 5-2 BIRKHOFF'S HEURISTIC ALGORITHM 84

TABLE 5-3 SIMULATION PARAMTERS 92

TABLE 5-4 MTC DEVICE AND PROXY-ENB PARAMTERS 92

TABLE 5-5 TRAFFIC CHARACTRASTICS OF MTC DEVCIES 98

TABLE 6-1 BSR BASED RESOURCE DIVISION ALGORITHM (BSR-RDA) 106

TABLE 6-2 DELAY BASED RESOURCE DIVISION ALGORITHM (D-RDA) 108

TABLE 6-3 SYSTEM PARAMETERS 109

TABLE 6-4 TRAFFIC PARAMETERS (MIXED TRAFFIC-CASE 1) 110

TABLE 6-5 TRAFFIC PARAMETERS (MIXED TRAFFIC-CASE 2) 112

TABLE 6-6 WLSE ALGORITHM 115

List of Figures

FIGURE 1-1 DIFFERENT M2M APPLICATIONS 4

FIGURE 1-2 IOT NETWORK ARCHITECTURE 6

FIGURE 1-3 AERIAL-ENB 10

FIGURE 1-4 NETWORK MODEL FOR DISASTER RELIEF 13

FIGURE 2-1 UPLINK RESOURCE GRID STRUCTURE [26] 18

FIGURE 2-2 FUNCTIONALITY OF LTE DYNAMIC PACKET SCHEDULING 19

FIGURE 2-3 SIGNALING EXCHANGE BETWEEN UE AND ENB 20

FIGURE 2-4 BUFFER STATUS REPORT LONG AND SHORT FORMATS 21

FIGURE 3-1 SCHEDULING TECHNIQUES CLASSIFICATION [33] 25

FIGURE 3-2 ENERGY PER BIT AS A FUNCTION OF THE RATE AND THE CHANNEL STATE [52] 31

FIGURE 3-3 BEARER SERVICES IN LTE NETWORK 35

FIGURE 3-4 MULTI-HOP COMMUNICATIONS TOPOLOGIES 44

FIGURE 3-5 TYPE-I AND TYPE-II RELAY 45

FIGURE 3-6 LAYER 3 IN-BAND VERSUS OUT-BAND RELAY DEPLOYMENT 47

FIGURE 3-7 RADIO FRAME CONFIGURATION FOR RELAY TRANSMISSION 47

FIGURE 3-8 RESOURCE PARTITIONING FOR RNS 48

FIGURE 3-9 DIFFERENT SCENARIOS FOR D2D SPECTRUM ALLOCATION 51

FIGURE 3-10 EXAMPLE ON SEARCH TREE BASED ALGORITHM 60

FIGURE 3-11 PRBS ALLOCATION IN ITRME ALGORITHM [132] 62

FIGURE 4-1 TARGET MOTION IN THE REGION OF INTEREST COVERED BY SENSOR NODES 71

FIGURE 4-2 AVERAGE NUMBER OF GENERATED PACKETS WITH RESPECT TO NUMBER OF DEPLOYED NODES 71

FIGURE 4-3 AVERAGE NUMBER OF PACKETS GENERATED EACH SENSING PERIOD 73

FIGURE 4-4 AVERAGE NUMBER OF PACKETS GENERATED EACH SENSING PERIOD $N=0.2$ NODE/M^2 73

FIGURE 5-1 M2M NETWORK MODEL 76

FIGURE 5-2 UPLINK RESOURCE NEGOTIATION PROCESS TO CALCULATE $WT_i(T)$ 85

FIGURE 5-3 SCHEDULING STEPS FOR MTC DEVICES DEPLOYED IN DISASTER AREA 86

FIGURE 5-4 PACKET GENERATION AND ON-OFF PRIOD FOR MTC DEVICE 86

FIGURE 5-5 LTE SCHEDULING MODEL USING M/M/C QUEUE MODEL 87

FIGURE 5-6 CONTINUOUS TIME MARKOV CHAIN MODEL FOR MTC LTE SCHEDULER 88

FIGURE 5-7 PROBABILITY OF USING MCS K BASED ON DSA RESOURCES SCHEDULING 89