Energy Efficient Routing for Multi-layer Design of Wireless Sensor Networks

Dissertation

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APPROVAL SHEET

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Verily all praise, grace and sovereignty belong to my Allah (*subha na hu wa ta'ala*), the Cherisher and Sustainer of the Worlds (Rabbul Aalameen), Most Gracious (Al-Rehman), Most Merciful (Al-Raheem) and Master of the Day of Judgment, whose bounteous blessings enable us to pursue and perceive higher ideas of life. He is he, who sent his prophets for the guidance of Human beings and Ginns. Darood and Salaam upon his last prophet, Muhammad (*Sal lal la hu a'lay he wa a'lay he wa'Sal'lam*), his family and his companions. They are the model of ultimate and eternal way of complete success in this world and hereafter in the form of followers of Quran: the ultimate manifestation of Allah's grace to man, the ultimate wisdom, and the ultimate beauty of expression: in short, the word of God (Allah).

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Last but not least, May Allah *subha na hu wa ta'ala* bestow his favor and blessings to all those who helped me and prayed for my success at any aspect of my Ph.D. especially to my Head of Department, Mr. Fazal Wahab, to ex-research coordinators, Dr. Imran Siddiqui, and current research coordinator, Dr. Muhammad Muzammal, to University management especially to ex-registrar, Respected Commodore (R) Mr. Mumtaz Raza for his special favor to build my confidence as a practicing Muslim and to staff of Computer Science Department especially to Afzal Tabassum, Muhammad Babar and Khan Muhammad. Aameen.

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DEDICATION

I dedicate this work to Hazrat Imam Hasan *razi Allah hu ta'la an'hu* who sacrificed his due status of being Khalifa for the wellness of Ummat-e-Muslima and as a reward, the sustainer of the world; Allah *subha na hu wa ta'ala* granted the role of Mahdi'at to one of his descendants (Muhammad Bin Abdullah - whose appearing to the world is very near) to bring the real peace in the world

Abstract

Wireless Sensor Network (WSN) has its applications from terrestrial to aquatic, from earth to cosmic, from agriculture to jungle and from home and offices to international borders. For it, tens to hundreds to thousands of nodes are deployed. So, the distance between the sources to destinations ranges from meters to kilometers that requires well-organized communication architecture with respect to software and hardware. Among constituents of communication architecture, routing is the most energy squeezing process. On focusing this issue, energy efficiency in the routing process is the ultimate goal of this dissertation that is achieved by setting some milestones. First target is to do a comprehensive analysis on energy aware routing in WSN and to present a detailed analysis on those factors that affect energy aware routing. This step gives backing for preparing the underpinning grounds for our further research. In a continuation of this work, clustered network architecture is analyzed and customized since it is extensively used by researchers for energy aware routing. However, more attention is required to ameliorate the energy consumption aspect of its cluster designing process. Hence, a novel design of clustered network architecture is introduced. The proposed design technique is innovative in its idea. Our novel layer-based hybrid algorithms for cluster head and cluster member selection come up to novel communication architecture. Since its substantial constituent is cluster designing, so it is named Multilayer Cluster Designing Algorithm (MCDA). The proposed design not only has an effect on lessening blind broadcasting, but also on decreasing the message exchange in a passionate way. It also encapsulates the beauty of efficient centralized decision making for cluster designing and energy-aware distributed cluster head selection and cluster member allocation processes. Comprehensive experimentations have been performed on the comparative analysis of MCDA with state-of-the-art centralized and distributed cluster designing approaches. Calculation of energy consumption at various aspects, number of designed clusters and number of packets broadcast during the cluster designing are the main performance parameters. It has been found that MCDA outperforms its competing algorithms with respect to the aforementioned parameters due to its multilayered synergistic mating approach. In the extension of this work, its constructive ramification; Extended MCDA is proposed to ameliorate the performance in network lifetime. Novel algorithms for time slot allocation, minimizing the cluster head competition candidates, and cluster member selection play underpinning roles to achieve the target. These incorporations in MCDA result in minimizing transmissions, suppressing unfavorable response of transmissions and near equal size and equal load clusters. Extensive simulations in NS2 are done to evaluate the performance of E-MCDA in energy consumption at various aspects, packets transmission, number of designed clusters, number of nodes per cluster and un-clustered nodes. It is found that the proposed idea optimistically outperforms the competition with MCDA and EADUC (Energy Aware Distributed Unequal Clustering). Next step is energy aware routing mechanism for WSNs is proposed. Constituents of this mechanism are analysis of MCDA for highlighting the parameters to be used for energy aware routing algorithm, Energy Efficient Cluster Head Rotation Technique and Energy Aware Routing Strategy for MCDA that is made up of inter-cluster and intra-cluster routing algorithms. Each constituent of this mechanism plays vital supportive role to other to achieve the target of energy awareness in the routing process. We conducted simulations in NS2 simulator to validate the performance of proposed scheme in comparison to TLPER (Threshold Based Load Balancing Protocol for Energy Aware Routing) and EADUC. Simulations

results demonstrate the performance efficiency of proposed scheme in terms of various metrics compared to similar approaches published in the literature.

Extended Abstract

WSN is a synergistic mating of wireless communication, sensor, and network technology. Apart from other inherited issues from wireless and Ad Hoc networks, induction of ideas in WSN are confined by its stringent constraint factors of computational power, memory and bandwidth. Along with this, round the clock offered limitation in the domain of WSN is energy. Its route cause is in-general battery operated and unattended deployment of WS nodes. Also, replenishment of battery is almost impossible due to inaccessible and far distant deployment of nodes in most of the applications. Although WSN has its deep inseparable indulgence in variety of applications, yet these limitations circumscribe it to attract more applications as well as using the existing protocols from its ancestor: Ad Hoc and wireless technology. So wireless protocols can not be adopted by Ad Hoc networks without customization and WSN is a special case of Ad Hoc network. Its functionalities are managed in a five layers suite namely physical, data link, network, transport, presentation, and application. Each aforementioned layer has its key inseparable role in the network functionalities which make up network's logical ingredients. These are inter-related and indispensable for a safe, secure, reliable, effective and efficient communication. Categorizing all the functions performed in/by WS node comes up under sensing, computation, reception and transmission. Among these, transmission is the hungriest function for energy that is majorly dealt by network layer where transmission is the roundabout of the routing process that is the key function of network layer. The key factors at network layer that effect on energy efficeint routing process are discussed in detail in Chapter 2. The routing protocol considering these aforementioned factors ultimately play a vital role in prolonging the network life time. The state-of-the-art solutions that are available in the literature to mitigate this effect are also critically discussed both in the scenario of flat and clustered network architecture. This work prepares the underpinning grounds for our journey of research work. This journey further covers the milestones of cluster designing, cluster member selection, cluster head selection, cluster head rotation, and intra-cluster and inter-cluster routing to achieve the goal of energy aware routing for homogenous WSN.

The proposed solution for energy aware cluster designing that is explained in Section 4.4 of Chapter 4 is the mature form of a series of solutions. It's very first form is published[1] where the idea of direct intra-cluster routing at some specific distance from sink is implemented in TOSSIM (Tiny OS Simulator) and also tested on hardware (MicaZ motes by CrossBow [1]). Its extended version is published in a journal[2] where the previous idea is improved along with its evaluation from different aspects in a number of experimentation works. This idea is also exploited in intra-cluster routing to increase the network life time at cluster level. Another extension[3] of the work presents the analysis of intra-cluster routing techniques (Direct hop routing (DR), Multihop routing (MR), MR-Case-I, MR-Case-II, MR-Case-III) in temperature sensing applications and battlefield applications scenarios. Until this publication, our all the

[1] R. A. Akhtar, A. A. Minhas and S. Jabbar, "AICR: Adaptive Intra-Cluster Routing For Wireless Sensor Network," Daejeon, Korea, 2009.

[2] R. A. Akhtar, A. A. Minhas and S. Jabbar, "Energy Aware Intra-Cluster Routing For Wireless Sensor Networks," International Journal for Hybrid Information Technology, vol. 13, no. 1, January 2010.

[3] H. Jan, A. Paul, A. A. Minhas, A. Ahmad, S. Jabbar and M. Kim, "Analysis of Intra Cluster Routing Techniques in Wireless Sensor Networks," Peer to Peer networking and Applications, Special Issue, Cloud, Grid, P2P and Internet Computing: Recent Trends and Future Directions, p. 13, 2014.

work has been to increase the network life time at cluster level through improving the communication in intra-cluster routing. Chapter 4 is the most mature state of this series of work. Endeavor is put at the gross root level and get its benefit in the form of overall network life time improvement. Though this work is not the direct extension of our previous work, yet the network architecture is the same and the idea with sufficient enhancement is used for designing of energy aware network architecture. To the best of our knowledge, this is first of its kind of research work on energy-efficient cluster designing approach with such detailed experimentation and in-depth analysis. To evaluate the claim, field experts reviewed our work for its evaluation and so it was published[4]. Its extended version is discussed in detail in section 4.6 of Chapter 4 with sufficient contributions for better improving the network life time. Secondly, proposed idea on cluster member selection and cluster head rotation that is included in our dissertation is the final product of our continuous research work in this aspect. Its first output comes in the form of a conference publication[5] and final work in the form of a Journal publication[6]. Sufficient improvements have been done in this work with carrying on its core idea of cluster head rotation. This produced paper is accepted[7]. Latest mature form of this run emerges as is presented in Chapter 5.

Third and last mile stone is inter-cluster and intra-cluster routing. Since routing at network layer is so far the most targeted problem among its other issues of the same layer, so producing a novelty at this aspect is a strenuous in itself. We have been analyzing, proposing and evaluating the routing algorithms for a flat network and clustered network as well. Solutions for the same are from conventional and non-conventional domains. Initial work on flat wireless sensor networks come up with the output in the form of three publications[8,9,10]. Proposed solutions for energy aware routing from bio-inspired computing domain are also published[11,12,13]. Later, we carry out our work on research articles with the solutions from the same domain especially

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[4] S. Jabbar, A. A. Minhas, A. Paul and S. Rho, "MCDA: Multilayer Cluster Designing Algorithm For Network Lifetime Improvement Of Homogenous Wireless Sensor Networks," *Journal Of Supercomputing,* vol. 11227, 2014.

[5] S. Jabbar, A. E. Butt, Najm-us-Sehr and A. A. Minhas, "TLPER: Threshold Based Load Balancing Protocol For Energy Efficient Routing In WSN," in *The 13th International Conference on Advanced Communication Technology (ICACT'11)*, Seoul, South Korea, 2011.

[6] Sohail Jabbar, Abid Ali Minhas, Anand Paul, Seungmin Rho, "E-MCDA: Extended - Multilayer Cluster Designing Algorithm for Network Life time Improvement of Homogenous Wireless Sensor Networks", International Journal of Distributed Sensor Networks, 2015

[7] S. Jabbar, A. A. Minhas and A. Paul, "Cluster Based Energy Aware Routing for Maximizing Throughput in Wireless Sensor Network," *Sensor Letters,* p. 8, 2014.

[8] S. Jabbar, A. A. Minhas and R. A. Akhtar, "SPERT: A Stateless Protocol For Energy-Sensitive Real-Time Routing For Wireless Sensor Network," Karachi, Pakistan, 2009

[9] S. Jabbar, A. A. Minhas, R. A. Akhtar and M. Z. Aziz, "REAR: Real-Time Energy-Aware Routing For Wireless Sensor Network," in *IEEE International Conference on Pervasive Intelligence and Computing*, Chengdu, China, 2009.

[10] A. A. Minhas, S. Jabbar, M. Z. Aziz and W. Mahmood, "QERT: Query-Based Energy-Aware Real-Time Routing For Wireless Sensor Network," in *ScalCom'2010*, Bradford, UK, 2010.

[11] S. Jabbar, R. Iram, A. A. Minhas, I. Shafi, S. Khalid and M. Ahmad, "Intelligent Optimization Of Energy Aware Routing In Wireless Sensor Network Through Bio-Inspired Computing: Survey And Future Directions," International Journal of Distributed Sensor Networks, vol. 2013, p. 13, 2013.

[12] S. Jabbar, A. A. Minhas, T. Rahseed and S. Rho, "Heuristic Approach for Stagnation Free Energy Aware Routing in Wireless Sensor Network," Ad Hoc Sensor Wireless Network (AHSWN), vol. 0, pp. 1-25, December 2014.

[13] Sohail Jabbar, Rabia Iram, Anand Paul, Abid Ali Minhas, Awais Ahmad, Muhammad Imran, "EASARA: Energy Aware Simple Ant Routing Algorithm in Wireless Sensor Network", Mathematical Problems in Engineering. 2015

from Ant Colony Optimization (ACO). As outcome, we got our work accepted and published in another journal[14]. This work is also for a flat network. Ultimately, we deduce from comprehensive literature survey that the clustered network is considered to be the most energy efficient architecture due to its ease in route discovery, fault tolerance, data aggregation and shortest possible end-to-end delay nature. So, research work inclines towards this energy aware architecture. Since long time, ideas in the literature on clustered network and routing over it is stuck and revolve around LEACH and its ramifications. Our arduous work adds number of publications in the research world[1,2,5]. This work leads us to a new horizon of ideas that had made this network more energy aware. Hence, our work on it glowed in the form of MCDA [section 4.4], E-MCDA [section 4.6] that over performed other contemporary solutions. The design of Multilayer Cluster Designing Algorithm is exploited for Forwarding Node selection, Inter and intra cluster routing, cluster head rotation and all the way to make this overall process energy aware. Constituents of this mechanism are; i) analysis of MCDA for highlighting the parameters to be used for energy aware routing algorithm, ii) Energy Efficient Cluster Head Rotation Technique, and iii) EAR for MCDA that is made up of inter-cluster and intra-cluster routing algorithms. Each constituent of this mechanism plays vital supportive role to achieve the target of energy awareness in the routing process. This work has also been published[13]. Chapter 5 is dedicated on it. Detailed discussion on its performance in comparison to existing state-of-the-art algorithms is made that is backed with experimental results.

[14] S. Jabbar, A. A. Minhas, M. Imran, S. Khalid and K. Saleem, "Energy Efficient Strategy for Throughput Improvement in Wireless Sensor Networks," Sensors, vol. 15, pp. 2473-2495, 2015.

Research Outcome

Based on our research work, the following research papers are published\accepted\submitted in credible international journals and conferences.

Major Contributions

Journals

1. **Sohail Jabbar**, Abid Ali Minhas, Shehzad Khalid, Kashif Saleem, "Energy Efficient Strategy for Throughput Improvement in Wireless Sensor Networks," Sensors, Vol. 15, pp. 2473-2495, **2015, IF 2.245** *(Published)*

2. **Sohail Jabbar**, Abid Ali Minhas, Anand Paul, Seungmin Rho, "MCDA: Multilayer Cluster Designing Algorithm for Network Life time Improvement of Homogenous Wireless Sensor Networks", Journal of Supercomputing, ISSN: 0920-8542 (Print Version), ISSN: 1573-0484 (Electronic Version), Journal No. 11227, Springer, **2014**. **IF 0.858** *(Published)*

3. **Sohail Jabbar**, Abid Ali Minhas, Anand Paul, Seungmin Rho, "E-MCDA: Extended - Multilayer Cluster Designing Algorithm for Network Life time Improvement of Homogenous Wireless Sensor Networks", International Journal of Distributed Sensor Networks, **2015**. **IF 0.665** (*Published*)

4. Hilal Jan, Anand Paul, Abid Ali Minhas, Awais Ahmad, **Sohail Jabbar**, Mucheol Kim, "Analysis of Intra Cluster Routing Techniques in Wireless Sensor Networks", Peer to Peer Networking and Applications, **2014**. **IF 0.632** (*Published*)

5. Raja Adeel Akhtar, Abid Ali Minhas, **Sohail Jabbar**, "Energy Aware Intra-Cluster Routing for Wireless Sensor Networks", International Journal for Hybrid Information Technology, Vol. 3, No. 1, January **2010** *(Published)*

Conferences

1. **Sohail Jabbar**, Ayesha Ejaz Butt, Najm-us-Sehr, Abid Ali Minhas, "TLPER: Threshold Based Load Balancing Protocol for Energy Efficient Routing in WSN", The 13th International Conference on Advanced Communication Technology (ICACT'11), 13th to 16th Feb **2011**, Seoul, South Korea *(Published)*

2. Raja Adeel Akhtar, Abid Ali Minhas, **Sohail Jabbar**, "AICR: Adaptive Intra-Cluster Routing For Wireless Sensor Network", (ACM), ICHIT'09, August 27th to 29th, **2009**, Daejeon, Korea *(Published)*

Extended Contributions

Journals

1. **Sohail Jabbar**, Rabia Iram, Anand Paul, Abid Ali Minhas, Awais Ahmad, Chaudhary Muhammad Imran, "EASARA: Energy Aware Simple Ant Routing Algorithm in Wireless Sensor Network", Mathematical Problems in Engineering. **2015. IF 0.762** (*Published*)
2. Kashif Amjad, Muhammad Ali, **Sohail Jabbar**, Majid Hussain, Seungmin Rho, and Mucheol Kim, "Impact of Dynamic Path Loss Models in an Urban Obstacle Aware Ad Hoc Network Environment," Journal of Sensors, vol. 2015, Article ID 286270, 8 pages, **2015**. doi:10.1155/2015/286270, **IF 1.108** (*Published*)
3. Moneeb Gohar, Jin-Ghoo Choi, Seok-Joo Koh, Kashif Naseer, and **Sohail Jabbar**, "Distributed Mobility Management in 6LoWPAN-Based Wireless Sensor Networks," International Journal of Distributed Sensor Networks, Vol. **2015**, Article ID 620240, **IF 0.665** (*Published*)
4. **Sohail Jabbar**, Abid Ali Minhas, Wajid Ali, Seungmin Rho, "Heuristic Approach for Stagnation Free Energy Aware Routing in Wireless Sensor Network", Ad Hoc & Sensor Wireless Networks, Old City Publishing, **2014. IF 0.478** (*Published*)
5. Awais Ahmad, **Sohail Jabbar**, Anand Paul, Seungmin Rho, "Mobility Aware Energy Efficient Congestion Control in Wireless Sensor Network", Special Issue on Advanced Convergence Technologies and Practices for Wireless Ad Hoc and Sensor Networks, International Journal of Distributed Sensor Networks. **2014**. **IF 0.665** (*Published*)
6. **Sohail Jabbar**, Rabia Iram, Abid Ali Minhas, Imran Shafi, Shehzad Khalid, Muqeet Ahmad "Intelligent Optimization Of Energy Aware Routing In Wireless Sensor Network Through Bio-Inspired Computing: Survey And Future Directions", International Journal of Distributed Sensor Networks, vol. 2013, Article ID 421084, 13 pages, **2013**. **IF 0.665** *(Published)*

7. Faisal Riaz, Imran Shafi, **Sohail Jabbar**, Shehzad Khalid, Seungmin Rho, "A Novel White Space Optimization Scheme Using Memory Enabled Genetic Algorithm in Cognitive Vehicular Communication", Wireless Personal Communications, Springer, **2015. IF 0.653** *(Published)*

Conferences

1. Majid Qayyum, **Sohail Jabbar**, Farooq Azam, Shehzad Rizwan, "Stagnant Free Ant Based Heuristic Routing In Wireless Sensor Network", International Conference on Collaboration Technologies and Systems (CTS'12 - CMSSN 2012), 21-25 May, **2012**, Denver, Colorado, USA *(Published)*
2. Rabia Iram, Muhammad Irfan Sheikh, **Sohail Jabbar**, Abid Ali Minhas, "Computational Intelligence Based Optimization of Energy Aware Routing In WSN", International Conference on Soft Computing and Applications (ICSCA'11) Held on 19th – 21st October, **2011**, San Francisco, USA *(Published)*
3. Abid Ali Minhas, **Sohail Jabbar**, Muhammad Zubair Aziz, Waiser Mahmood, "QERT: Query-Based Energy-Aware Real-Time Routing for Wireless Sensor Network", (IEEE), ScalCom'2010, 29th June – 2nd July, **2010**, Bradford, UK *(Published)*
4. **Sohail Jabbar**, Abid Ali Minhas, Raja Adeel Akhtar, Muhammad Zubair Aziz, "REAR: Real-Time Energy-Aware Routing for Wireless Sensor Network", PICom09, (IEEE), December 12-14, **2009**, Chengdu, China *(Published)*
5. **Sohail Jabbar**, Abid Ali Minhas, Raja Adeel Akhtar "SPERT: A Stateless Protocol for Energy-Sensitive Real-Time Routing for Wireless Sensor Network", (IEEE), ICICT'09, August 15th to 16th, **2009**, Karachi, Pakistan *(Published)*
6. **Sohail Jabbar**, Abid Ali Minhas, "Energy-Aware Real-Time Communication in Wireless Ad-Hoc Micro Sensors Network", (ACM), FIT 2009 Ph.D. Symposium, December 16-18, **2009**, Pakistan *(Published)*

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List of Abbreviations

Here is given a list of abbreviations that are frequently used in this dissertation.

Table 1: Abbreviations Used in Dissertation and their Description

Abbreviation	Description
CH	Cluster Head
ACH	Assistant Cluster Head
BCDCP	Base-Station Controlled Dynamic Clustering Protocol
BS	Base Station
CAN	Cluster based Network Architecture
CCD	Centralized Cluster Designing
C-LEACH	Centralized-Low Energy Adaptive Clustering Hierarchy
CM	Cluster Member
DARPA	Defense Advanced Research Projects Agency
DCD	Distributed Cluster Designing
DSSS	Direct Sequence Spread Spectrum
EADUC	Energy Aware Distributed Unequal Clustering
EAR	Energy Aware Routing Strategy
ECHeaRT	Energy Efficient Cluster Head Rotation Technique
E-MCDA	Extended - Multilayer Cluster Designing Algorithm
FS	Forwarding candidate neighbor Set
ISM	Industrial, Scientific, and Medical
LBT	Load Balance Threshold
LSN	Large Scale Network
MANET	Mobile Ad Hoc NETwork
MCDA	Multilayer Cluster Designing Algorithm
MWSN	Mobile Wireless Sensor Network

NS2	Network Simulator Version 2
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
RTT	Role Transfer Threshold
SANET	Static Ad Hoc NETwork
SWSN	Static Wireless Sensor Network
TCH	Tentative Cluster Heads
TL-LEACH	Two Level - Low Energy Adaptive Clustering Hierarchy
TLPER	Threshold Based Load Balancing Protocol for Energy Aware Routing
TOSSIM	Tiny OS Simulator

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CHAPTER 1

1 Introduction

A typical wireless sensor node consists of a mote and a sensor board along with power supply and memory devices. A mote is responsible for processing, storage, and power supply and data communication with other nodes or base- station while sensing task is on the part of the sensor board. The representation of the sensor board to be plugged in MICA mote is shown in Figure 1.1.

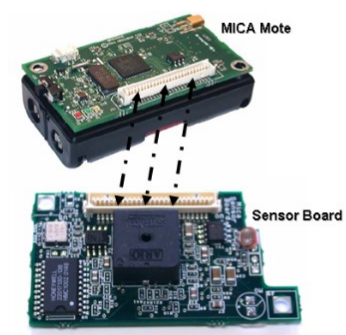


Figure 1.1 : MICA Mote Plugged into Sensor Board

Sensor nodes are deployed either in a random fashion or planted manually according to the requirements and available situations. In the outdoor environment; the Line of Sight communication range is 75 to 100 m with ½ wave dipole antenna and in the indoor environment; the communication range is 20 to 30 m with ½ wave dipole antenna [2]. Multiple communication bands of 433 MHz, 869-915 MHz and 2.4 GHz and each with multiple channels for supple solution of different application requirements are available. Radios are half-duplex bidirectional. Signal is transmitted with a maximum data rate of 250 Kbps depending upon the choice of radio and configuration. Communication data security is obtained by Direct Sequence Spread Spectrum (DSSS) technique. Data dissemination from source to sink and vice versa usually requires transit nodes' positioning information either through GPS-free localization [3], relative localization [4] or absolute localization [5] techniques. Apart from MICA mote by CrossBow [1], there is also a long list of sensor nodes available in the market from various manufacturers. Table 1.1 enlists some well-known sensor nodes with their short description [6].

Table 1.1: List of Well Known Sensor Nodes with their Brief Description

Sensor Node	Description
BTnode rev3 [7]	It is Based on an Atmel AVR microcontroller, a Bluetooth, and a Chipcon CC1000 radio. A BTnode rev3 is a Crossbow Mica2 Mote with more SRAM (256K) and an additional Bluetooth radio.
EyesIFXNode [8]	It is the first commercial hardware release of the EyesIFXNode Family developed by Infineon Technologies. This node is built from TI MSP430F1611 Microcontroller, IFX TDA5250 radio transceiver, AT 45DB041B external storage, light sensor (NSL19M51), and temperature sensor (LM61 Temperature Sensor).
G-Nodes [9]	It is Based on ultra-low power wireless sensor module based on a Texas Instruments MSP430F2418 microcontroller and Texas Instruments CC1101 packet radio. Temperature sensor and battery voltage readout integrated into the microcontroller. Fast wake up from sleep (<2μsec).
Fleck 3 [10] [11]	It is developed at CSIRO ICT Centre, Australia since the end of 2003. It provides Integrated solar charging, Long-range radio based on 430 and 915MHz radio chips (nRF903 and nRF905) from Nordic Semiconductor. Its range is over 1000m with a λ/4 whip antenna. It uses Atmega 128 and nRF905 radio.

Sun Spot [12]	It is ARM9 and CC2420 based platform running JAVA with 32 µA standby current. This is achieved by a secondary AVR based wake-up processor for the more power hungry ARM9. The key to this platform is an additional Atmega48 that runs the RTC and wakes up the main CPU within a ~msec. Power consumption is 36 micro amps during deep sleep (ARM is turned off, AVR still runs real time clock, and the ARM SRAM is buffered)
Tmote Sky [13]	It is Ultra low power IEEE 802.15.4 compliant wireless sensor module based on a TIMSP430 and Chipcon CC2420 radio. Also named Telos B. It has TI MSP430F1611 microcontroller at up to 8 MHz, 250kbps 2.4 GHz Chipcon CC2420 IEEE 802.15.4 Wireless Transceiver, On-board humidity, temperature and light sensors, and Fast wake up from sleep (<6usec).
T-Nodes [14]	It is developed by SOWNet Technologies. It has 1 year battery life on AA batteries with power management, 868, 433, 915, or 315 MHz multi-channel radio transceiver and Light, temperature, RH, barometric pressure, acceleration/seismic, acoustic, magnetic, GPS, and other sensors available, also supporting supplied custom sensors or integration thereof.
FireFly [15]	FireFly is a low-cost wireless sensor network platform capable of data acquisition, processing & multi-hop mesh communication. Each battery-operated node delivers a life time of 1.5-2 years on 2 AA batteries. Each FireFly node features an IEEE 802.15.4 transceiver capable of short-range (50-100m) data communication with a maximum raw data rate of 250Kbps. An 8-bit microcontroller processes data from on-board light, motion, audio, temperature and acceleration sensors.
WiSense [16]	It has IEEE 802.15.4 low-power radio, Powered by 16-bit microcontroller from Texas Instruments. It has onboard temperature sensor and light sensor and Provision to add more.

Required environmental, physical quantity is sensed by the source node(s) and is disseminated through the network up-to the data fusion center or base station. The information so obtained can be used in Ethernet based networks as well as worldwide by connecting the sink to the IP-based network [17], [18]. In all of these operations, special techniques should be employed tactfully to manage the constraint resources (energy, bandwidth, computation, and processing) of WSN. Among these constraint resources, energy conservation is the core issue. The major energy sources of these miniature sensor nodes are either energy storage devices like batteries or energy scavenging devices like vibration or a combination of both. Solar radiation is the most abundant energy source and yields around 1mW/mm^2 (1J/day/mm^2) in full sunlight or 1µW/mm^2 under bright indoor illuminations [19]. Vibration has been proposed as an energy source that can be scavenged. So for as energy consumption is concerned, sensor acquisition can be achieved at 1 nJ per sample, and modern processors can perform computation as low as 1 nJ per instructions. Current transmission techniques (e.g. Bluetooth) consume about 100 nJ per bit for a distance of 10m to 100m, making communication very expensive compared to acquisition and processing [19].

Stateless and light-weight protocols, dynamic power adjustment and different power saving modes are excellent candidate solutions in order to minimize computation and to save transmitting, receiving, sensing and processing power to add more life to WSN in its constraint resource environment. In wireless sensor network, nodes are uniformly or stochastically (randomly) deployed in the target region. Interconnection of nodes in a decentralized fashion without following any pre-existing infrastructure is named as Ad Hoc network.

In wireless sensor network, nodes might be scattered randomly across the region for decentralizing the network traffic and computational load to increase the coverage, capacity, and reliability. This distributed network scenario also comes up with avoidance of a single point of failure. As every node in WSN either acts as a sensor, router or gateway node which has its computing responsibility resulting in distributed computing paradigm. Uniform or stochastic deployment of wireless sensor nodes comes up with a distributed architecture of non-directed graph where nodes are vertices, and the edges represent the communication link between them. In the distributed network of sensor nodes, each computational autonomous entity (node) acts/can act as a sensor as well as router. This entity establishes communication links with other nodes in its footprint (communication range) through Omni-directional full duplex antenna. This cooperative interaction of neighboring nodes expands up to a whole network giving birth to its self-configuring, self-organizing, self-adaptive and self-synchronizing capabilities. This technology that is encapsulating such a long list of qualities is now in action with lots of mind blowing applications by indulging it in various fabrics of life. The cradle of WSN research was first nourished by Defense Advanced Research Projects Agency (DARPA) through the military applications.

It continued to explore this technology by funding a number of prominent research projects e.g. Smart Dust [20], Network Embedded System Technology [21]. Some other important real world applications/projects of WSN [22] are Wave Monitoring [23], Ocean Water Monitoring [24], ZebraNet [25], Cattle Herding [26] and neuRFon [27]. This emerging technology has also its applications in Habitat Monitoring [28], Traffic Surveillance [29], Ocean Water and Bed Monitoring [30], Wildlife Monitoring [31], Cold Chain Monitoring

[32], Landslide Detection [33], Vital Sign Monitoring [34], Tracking Vehicles [35], and Living and Residential Monitoring [36]. A list of various sensor network's world fame projects with their short description, related publication and information link is given in Table 1.2.

Table 1.2: Real World WSN Projects with Their Short Description, Related Publications and/or information Link

Project	Purpose of project	Related Publication and/or information link
Sickbuilding	Wireless sensor networks in sick buildings	[37]
Sensorscope	Sensor Networks for Environmental Monitoring	[38] [39] [40] [41]
MIT River Hunduras	Sensor Networks for Physical Event Monitoring: Flood Prediction in Central America	[42] [43]
Smart' water quality sensor network	Smart sensors for monitoring water quality and catchment health	[44]
PermaSense	To use in remote areas with harsh environmental monitoring conditions	[45] [46]
Water for a Healthy Country	Dairy water use in Australian dairy farms	[47] [48]
Airy Notes	To monitor environmental condition in Shinjuku Gyoen Garden	[49] [50]
Redwood Forest	Study of California's state tree	[51] [52]
Volcanoes	Monitoring eruptions of active and hazardous volcanoes	[53] [54]

A Typical WSN Application at international border is shown in Figure 1.2.

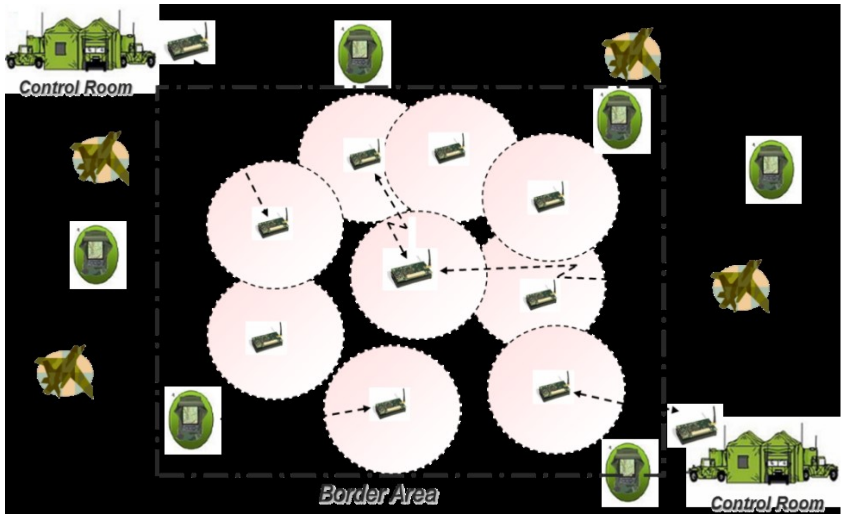


Figure 1.2: WSN Application at Border Area

Another synergistic mating of wireless network (for data acquisition) and wired network (data distribution) is graphically modeled in Figure 1.3. Underwater sensor network that is typically based on ultrasound is also a key application of WSN [55].

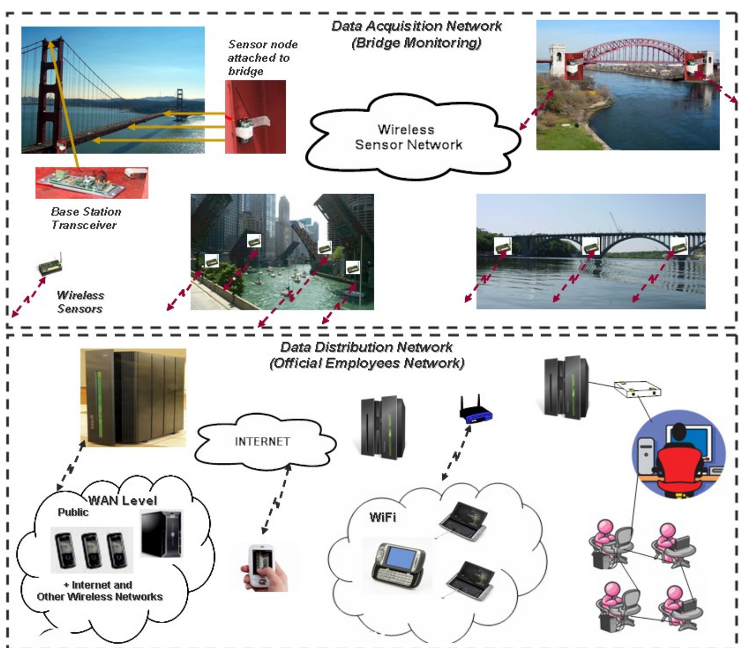


Figure 1.3: Synergistic Mating of Wireless Network (for Data Acquisition) and Wired Network (for Data Distribution)

With the increasing emergence of WSN, various organizations participated in the arena of defining standards for it. Though a long list of standards for WSN is available, yet here a brief description of most well-known related works is given.

IEEE 802.15.4 wireless technology focuses on the standardization of Physical and MAC layer of OSI protocol stack. Its core system consists of a Radio Frequency (RF) transceiver and the protocol stack. It is featured with low complexity, low data rate in transmission, low cost, and low power consumption. These all characteristics make this technology well suited for applications of Wireless Sensor Networks. The 802.15.4 physical layer operates in three different unlicensed bands; 868 [MHz] band (only a single channel), 915 [MHz] band (Ten Channels), 2.4 [GHz] ISM band (Sixteen Channel) that are commonly known as Industrial, Scientific and Medical (ISM) bands. In the case of interference in the shared unlicensed bands, different spread spectrum techniques are used [56]. A special energy saving feature of IEEE 802.15.4 compliant devices is their switching between active, inactive and sleeping modes. This standard allows some devices to operate with both the transmitter and the receiver inactive for over 99% of the time. Although the transmission range is very limited, yet multi-hop communication fashion helps to overcome it [57].

ZigBee is a Well-known standard for above 802.15.4 by ZigBee Alliance. It also gives mesh network capabilities to 802.15.4 applications. Mesh networking allows reconfiguration around blocked paths by hopping from node to node until the data reaches the destination [22].

6LowPAN (IPv6 over Low-Power WPANs) is an open standard by Internet Engineering Task Force (IETF) in 2007 in comparison to ZigBee over 805.15.4. IP for Smart Objects

(IPSO) Alliance is promoting the use of 6LowPAN and embedded IP solutions in smart objects. This standard specifically focuses on utilizing the IPv6 on top of low power, low data rate, low cost PAN. The charter of 6LowPAN working group is to define how to carry IP-based communication over IEEE 802.15.4 links while conforming to open standards and assuring interoperability with other IP devices [58]. This makes it different from ZigBee since the later needs 802.15.4/IP gateway to interact with an IP network. For an application with small packet size and no need to interface with IP devices, ZigBee is preferred over 6LowPAN [59] [60].

Impulse Radio-UWB (IR-UWB) an extension of UWB and relies on ultra-short waveforms is specially designed for the applications of WSN. It is free from sine-wave carriers and does not require IF processing due to their operation at the baseband [61]. The IR-UWB technique has been selected as the PHY layer of the IEEE 802.15.4a Task Group for WPAN Low Rate alternative PHY layer. Two optional PHYs makeup the baseline of 802.15.4a. One of these two is UWB impulse that operate in unlicensed UWB spectrum. Other one operate in unlicensed 2.4 GHz spectrum. Former option is supposed to deliver communications and high ranging of precision [62].

This concise introduction of WSN portrays an ever growing research area that have great motivation for current and future researchers. Its extension to give rise to state-of-the-art technologies i.e. Linear Wireless Sensor Network [63], Internet of Things [64], etc. is a splendid reflection of enhanced penetration in future technologies. In a continuation of this section, the next part elaborates the motivation for energy efficient routing for multi-layer design of WSN to develop basis for scientific focus of this dissertation.

1.1 Motivation

Although WSN has its deep inseparable indulgence in variety of applications as are elucidated in previous paragraphs, yet less computing power, constrained energy and limited bandwidth circumscribe it to attract more applications as well as using the existing protocols from its ancestor: Ad Hoc and wireless technology. IEEE 802.11 subcommittee adopted the term Ad Hoc network in the late nineties [65]. Ad Hoc network inherited some of the tribulations of wireless communication network like unreliable time in-varying asymmetric channel, improperly defined coverage boundary, lossy link, etc. In addition to this, location awareness, multihop environment, dynamically changing topology, node and channel vulnerability issues in Ad Hoc network environment have their messy contribution in this knotted portfolio and to lengthen this tribulations list. So, on the basis of above mentioned disparities, algorithms designed for wireless networks and Ad Hoc networks (Location-Aided Routing [66], Dynamic Source Routing [67] , Ad Hoc On demand Distance Vector [68]) are not suitable for WSN and need customization and improvement.

So wireless protocols can not be adopted by Ad Hoc networks without customization due to the aforementioned grounds. Similarly, WSN also comes up with some differences from its close ancestor, Ad Hoc Network like densely and randomly deployed nodes, unattended operation for a long period and other constraint resources. Also in WSN, in addition to most of the aforementioned issues, network partitioning, localization, calibration, data fusion, aggregation and dissemination, coverage, self-organizing and self-administration, scalability, load balancing, node clustering, topology management, end-to-end delay constraint routing, security and privacy, heterogeneity, and other energy, memory, power and bandwidth constraints are the active challenges.

In the closer view, node scheduling, hole problem, avoiding and coping with void node areas, node failure and QoS relating factors are under great concentration of researchers [69]. From sensing to receiving at Base Station (BS) through communication and processing, the entire network ingredients, their interaction and functionalities are divided into five different layers model that is the hybrid of OSI seven layers and four layers of TCP/IP layers models [70]. Figure 1.4 shows the comparison of these three models. Each layer has its long list of functionalities and related issues that is inviting the researchers to engage themselves to work for their better performance leading to the best.

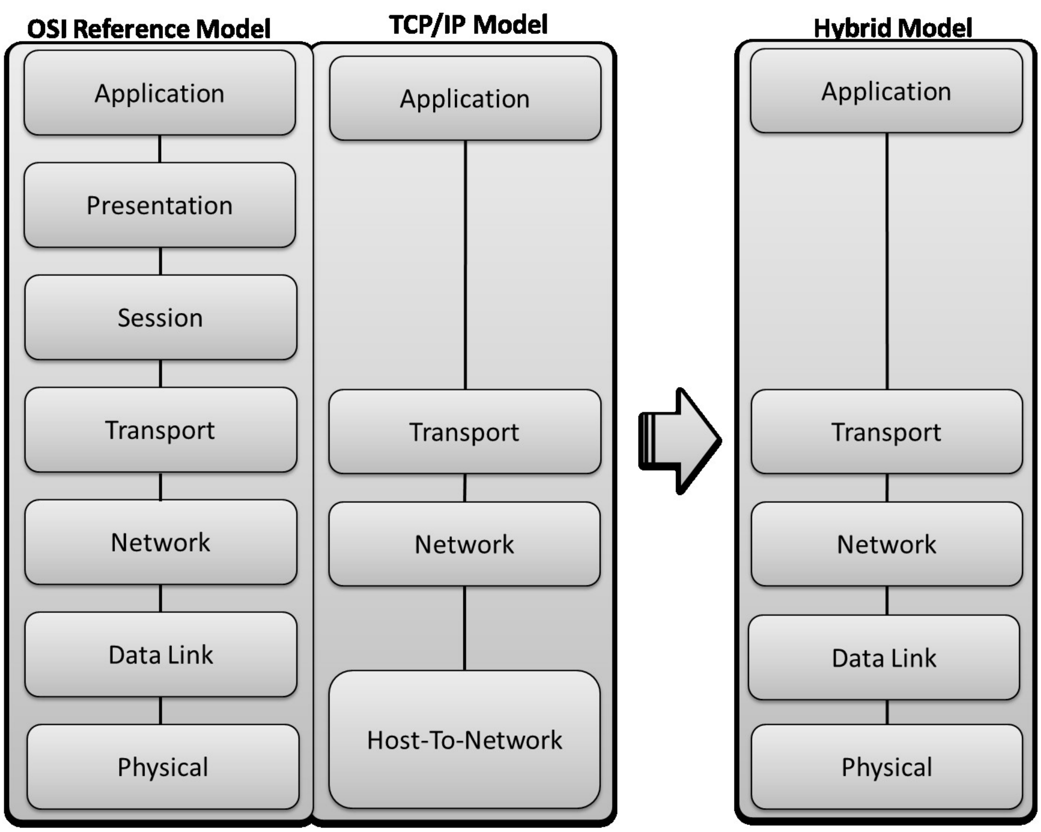


Figure 1.4: Comparison of OSI Reference Model, TCP/IP Model, and the Hybrid Reference Model.

Table 1.3 demonstrates the five working layers of WSN, their related issues and the references of key survey articles thereon. Apart from this five layered architecture, middle layer or cross layer issues also have their distinguished Importance and play a vital role in an efficient network performance.

Table 1.3: List of hot research topics at different Layers in WSN

Layer	Issues	References
Physical Layer	Frequency Selection/Carrier Frequency Generation, Data Encryption, Modulation and Demodulation, Channel Coding/Modeling, Signal Detection, Antenna Sensitivity and Transceiver Design, Wave Propagation, Spread Spectrum Communication, Packet Transmission and Synchronization, Channel Coding, Multiplexing / De-multiplexing,	[71] [72]
Link/MAC Layer	Hidden Node Problem, Congestion Control, Error Control, Medium Access , Radio Transmission Power Control, Link Quality Estimation, Network Security, Bandwidth Utilization, Localization and Positioning, Time Synchronization, Scalability, Topology Control, Naming and Addressing	[73] [74] [75]
Network Layer	Route Discovery, Forwarding Node Selection, Neighbor Discovery, Re-route Discovery, Void-Bridging, Energy Conservation, Network Security, Node Operational Life time, Energy Efficient Cluster Designing, Throughput Improvement	[73] [76] [77] [78] [79] [80] [81]
Transport Layer	End-to-End Retransmission based Error Control, Event-to-Sink Transport Reliability, Sink-to-Sensor Transport Reliability, Congestion Control, Transmission Power Control, Effect of Mobility on route stability	[82] [83]
Application Layer	Physical topology utilized, query generation and process in different schemes of data aggregation and data generation in flat or in clustered networks.	[72] [84] [85]

Each aforementioned layer has its key inseparable role in the network functionalities ranging from physical environmental sensing to generation of suitable binary bit stream, from end-to-end link reliability to error detection and correction, from node addressing to packet routing, from medium access to safe and secure transmission, from signal generation to modulation and multiplexing and ultimately dissemination of transmitted data to the destination through transient node. Each of these network's logical ingredients is inter-related and indispensable for a safe, secure, reliable, effective and efficient communication between the interacting nodes of near or far distant networks. All of these logical ingredients are measured and finalized at node and utilize its resources.

Further-over, WSN is a synergistic mating of wireless communication, sensor, and network technology. Apart from other inherited issues from wireless and Ad Hoc networks as mentioned in the previous section, induction of ideas in WSN are confined by its stringent constraint factors of computational power, memory and bandwidth. Along with this, round the clock offered limitation in the domain of WSN is energy. Its route cause is in-general battery operated and unattended deployment of WS nodes. Also, replenishment of battery is almost impossible due to inaccessible and far distant deployment of nodes in most of the applications. Since the node energy is the most participating factor in the completion of any related task. So, the presenting solutions in WSN domain consider this very factor. Categorizing all the functions performed in/by WS node comes up under sensing, computation, reception and transmission. Energy consumption in transmission of a bit to 10m to 100m is equal to energy consumption in acquisition and computation of 100 bits.

Hence, appealed that transmission is the hungriest function for energy that is dealt by MAC layer and network layer. At MAC layer, transmission is only involved in safe access of medium while, at network layer, transmission is the roundabout of the routing process that is the key function of network layer. Increased communication distance and bigger packet size add more energy cost in the transmission function. Transmission, computation, and reception are largely involved in maintaining network table, route discovery. Re-route discovery, data collection, broad casting, forwarding node selection, etc. Hence, the role of network layer is direly highlighted in data communication process.

In view of all the above discussion, efforts are put and ideas are floated to conserve the precious constraint resource of energy at this layer through minimum broadcasting, smart forwarding node selection mechanism, stateless path finding, route maintaining, and re-route discovery algorithms, and etc. Decreasing the transmitted packet size using data fusion and data aggregation techniques is another effort to conserve the energy at network layer. To have a closer look, the key factors at network layer that affect on routing process and must be considered during the design of routing algorithm are: Broadcasting, Beacon Message Exchange, Probe Messaging, Rout Discovery, Forwarding Node Selection, Re-route Discovery, Void-Bridging Strategies, Frequent Updating of Neighbor Table and Routing Table. In Case of Clustered Network, key factors are Cluster Designing, Cluster Head Selection, Cluster Head Rotation, Cluster Redesigning, Forwarding CH Selection, Node Level Calculation and Processing etc. In the case of mobile Ad Hoc network, conversing on energy in the aforementioned constituents of the routing process become more challenging as well as adding other dynamic factors like considering the dynamic topology. The routing protocol considering these aforementioned factors ultimately play a vital role in prolonging the network life time. In the second chapter, the analysis of these above mentioned factors is presented in detail for preparing the underpinning grounds for our further research.

In the remainder of this first chapter, first the problems are stated that are investigated in this dissertation under the head of scientific focus. In the subsequent section, outline of the rest of our dissertation is briefly summarized.

1.2 Scientific Focus

Cluster based network architecture is selected for the undergoing research work to improve the network life time. Although a multitude of comprehensive studies has been under taken and a lot of related literature is available on it, yet improvements are still needed at various aspects of this fashion of network design. Following are the key constituents of better energy aware Cluster based Network Architecture (CNA) that need to be targeted to ameliorate the network life time and are inviting the researchers to work thereon.

1.2.1 Cluster Designing

Cluster Designing techniques can be categorized under centralized and distributed approaches. In Centralized Cluster Designing (CCD), the deployed nodes communicate their information to the Base Station (BS). This information can be node energy level, node degree (number of neighbors of a node that is also called as node density), geographical location, and output of some decision metrics' calculation depending upon the underlying CCD algorithm [86]. This information communication can be direct or multi-hop using transient nodes depending upon the network scale. Base station applies some clustering algorithm; K-Nearest Neighbor [87], K-Means [88], Centroid [89], or Affinity Propagation [90] etc., for the selection of cluster head and communicates the decision with the deployed network nodes. CH then broadcasts its status. Listener nodes affiliate themselves to the most suitable CH. Proximity to CH, distance of CH to BS, energy, load or the combination of these can be the affiliation decision parameters. In Distributed Cluster Designing (DCD), nodes communicate the values of selection metric(s) to each of their neighboring nodes. The node that has the best value of selection metric(s) is designated as the Cluster Head (CH). CH advertises its status which helps the nodes to join it as cluster members depending upon Received Signal Strength Indicator (RSSI) or any other assignment metrics [17] that is almost the same as stated before in case of CCD.

Workable solutions with multilayer architecture are proposed for the aforementioned most energy demanding part of cluster based wireless sensor networks which is innovative in its design and communication architecture. Their description is given below:

a) Proposed algorithm for cluster formation uses multilayered approach comprising of first flat layer in the footprint of the base station and the subsequent clustered layers. Designing of the former layer is initiated centrally whilst distributed fashion is applied in the designing of later. Its constituents come up to energy efficient cluster designing not only lessening broadcasting but also decreasing the message exchange in a passionate way. It also encapsulates the beauty of efficient centralized decision making for cluster designing and energy aware distributed cluster head selection and Cluster member allocation process.

b) Next proposed idea is the constructive ramification of Multilayer Cluster Designing Algorithm to ameliorate the performance in network life time. Novel algorithms for time slot allocation, minimizing the cluster head completion candidates, and cluster member selection\node affiliation to cluster the head play underpinning roles to achieve the target. These incorporations in MCDA result in minimizing transmissions, suppressing unfavorable response of transmissions and near equal size and equal load clusters.

1.2.2 Routing algorithm design for CNA with Cluster Head Rotation strategy

Among the communication models in clustered architecture, direct hop fits better for small scale networks where the nodes communicate directly to the base station [91] [92]. The typical fashion of direct hop communication from CH to BS in V-LEACH [93] is shown in Figure 1.5 where CH is collecting data from cluster member nodes and communicating it directly to control room/base station.

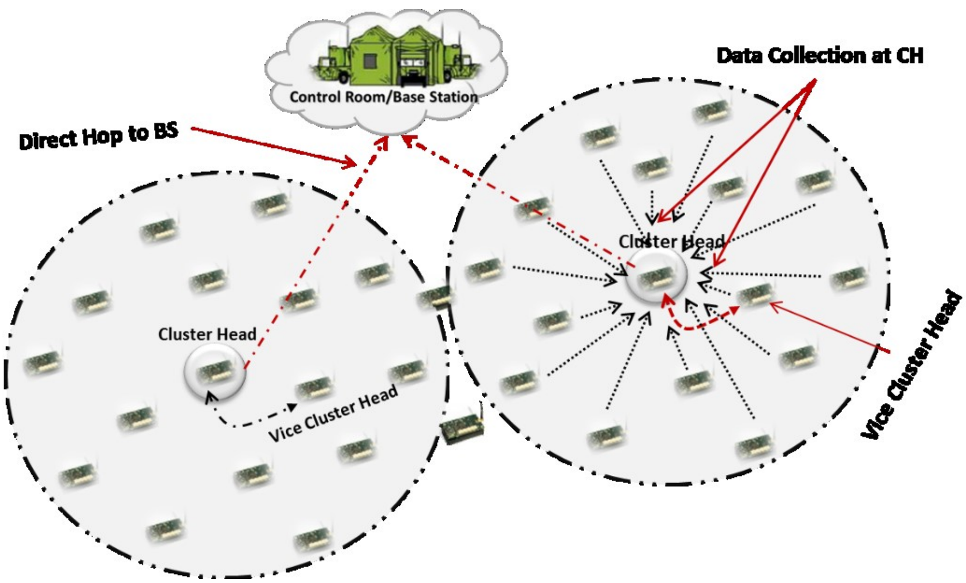


Figure 1.5: Direct Hop Routing Approach in V-LEACH

In PEGAGIS [94], data is collected at any of the randomly selected nodes in the chain. From which it is directly transmitted to the BS. In such communication style, transmission power of a node limits the network size. Since the network size is a function of maximum transmission range of a node. More-over, in direct hop communication there is no need of establishing the route and hence no complex routing protocol. For large scale networks, multi-hop communication model provides scalability through the transient nodes assistance to destine the data to far distant placed BS [95]. Various approaches in multi-hop transmission from CH to BS exist. A bit extension in the limitation of LEACH [91] is proposed in Two Level – LEACH (TL-LEACH) [96] algorithm by making primary and secondary CHs. Collected data at resident CH called -secondary CH is transmitted to the primary CH which transmits it directly to the BS. Figure 1.6 depicts this style of working of TL-LEACH.

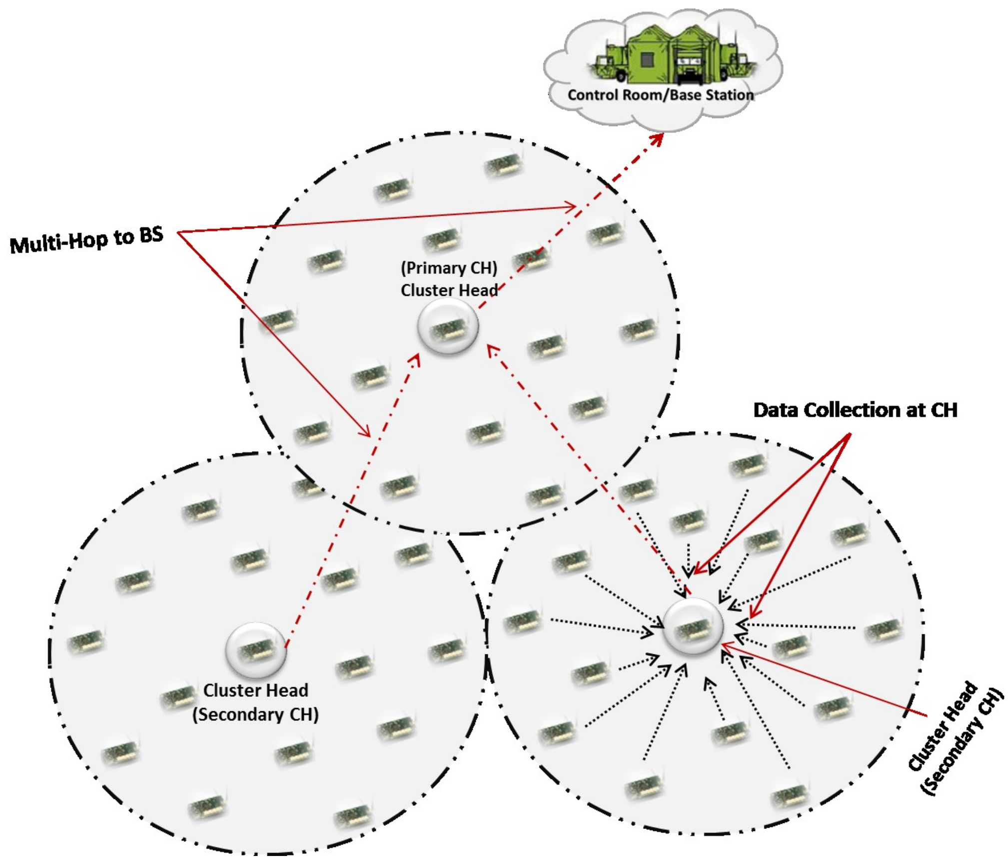


Figure 1.6: Multi-hop Routing Approach in TL-LEACH

Multi-hop technique adapted in Base-Station Controlled Dynamic Clustering Protocol (BCDCP) [86] eliminates the limitation of one or two hop communication from CH to BS. The collected data at CH is sent to the BS through multiple transient nodes depending upon the distance to BS. In such scenario, routing protocol is more complex and needs well planning. In this way of CH to CH multi-hop transmission mode, neighboring CHs must be in the communication range of each other for successfully sending data. An assistant CH for its solution is introduced in [17]. Various techniques of electing the cluster heads and forwarding node selection are adopted in the literature. Some important among those have been presented in the next chapter; *'Analysis of Factors Affecting Energy Aware Routing'*.

Our proposed idea is on energy aware routing mechanism (EAR4MCDA) for WSNs. Constituents of this idea are i) analysis of MCDA for highlighting the parameters to be used for energy aware routing algorithm, ii) Energy Efficient Cluster Head Rotation Technique (ECHeaRT) and iii) Energy Aware Routing Strategy for MCDA that is made up of inter-cluster and intra-cluster routing algorithms. Each constituent of this proposed idea plays vital supportive role to other to achieve the target of energy awareness in the routing process.

1.3 Contributions of Dissertation

The research work that is performed under the head of dissertation and explained in detail throughout this dissertation has its number of contributions in research world. Among the following enumerated points, 1st, 2nd and 3rd contributions are discussed in section 4.4, 4th, 5th and 6th contribution is elaborated in section 4.6. 7th and 8th contributions are explained in section 5.2 of this dissertation. These contributions are as follows:

1. A new synergistic mating technique of communication architecture is introduced. It shows the advantages of both flat and clustered network. Flat layer at the neighborhood of BS up to first hop serves to keep the nodes alive for longer and

provide multipath to BS. Whereas in the subsequent layers, the maximum advantages of clustered network can be gained.

2. An innovative technique is introduced to develop the communication architecture in competing to pure cluster base architecture. The multilayered approach of proposed algorithm, MCDA encompasses the hybrid communication design of direct and multi-hop routing. It has made it more energy efficient. Such a practice has already been proven energy efficient in intra-cluster routing [97]. More-over, this technique helps in fixing the issue of early death of cluster heads that are in neighbor of BS.
3. The multi-layer approach of proposed solution encapsulates the energy aware network design and efficient route discovery from source to destination. Also the rotation or re-assignment of forwarding node selection has already been planned in the design phase of proposed communication architecture. This multi-objective design has big contributions in prolonging the network life time.
4. In the extended version of cluster designing idea presented in MCDA, $T_{wait(t_i)}$ parameter is introduced that has following benefits. Also a scenario for better demonstration of clustering layer design in E-MCDA is depicted, explained and discussed.
   a. Minimizing the message broadcast during selection of decision maker nodes $Node_{(dm)}$ and also in the election of cluster heads.
   b. Incorporation of $T_{wait(t_i)}$ in designing of clustering layer significantly modifies the proposed solution in MCDA that makes clear difference in E-MCDA from MCDA.

5. In cluster member selection phase of E-MCDA, a new '*Node Affiliation Algorithm*' is introduced that is aiming to design near equal size clusters and hence with near equal load. Also A scenario for better demonstration of cluster member selection in E-MCDA is depicted, explained and discussed.
6. Proposed algorithms whose some aspects have been implemented and evaluated in our previous work [17] [98] are used to exploit the architecture of MCDA to get the maximum advantages out of clustered WSN.
7. The crux of routing that works over flat network is optimal FN selection among available Forwarding Node Set (FNS) whose information is kept in neighbor table. Proposed strategy; Energy Aware Routing (EAR) has successfully implanted the same idea in clustered network with suitable customization and modification by considering the energy awareness aspect. Enlisting candidate decision maker nodes in neighbor table during cluster designing process, introduction of two threshold levels of CH's energy are major among those.
8. Same style of FN selection as is mentioned in previous point is subjugated for rotation strategy of CH and FN as well. This serves a great deal in conserving energy and hence improving the network life time

1.4 Organization of the Dissertation

The remainder of the dissertation is organized as follows.

- Chapter 2 investigates the routing function of network layer in WSN and identifies the factors that effect on its energy efficiency aspect. The state-of-the-art solutions that are available in the literature to mitigate this effect are also critically discussed both in the scenario of flat and clustered network architecture. Modeling of each factor is also presented for better understanding.

- Chapter 3 comprehensively discusses the state-of-the-art related work. Cited literature is divided into three parts related to three addressed questions in the dissertation; cluster designing, cluster head and cluster member selection and CH rotation and routing in clustered network. Each sub section is concluded with required improvements in the available research work to make the network energy aware. In the last subsection, comparative analysis of cluster based routing algorithms on various parameters is given in a tabular format. This gives a summarized view to state-of-the-art related literature. At the end of chapter, our contribution of the dissertation in the research world is mentioned. This chapter is comprised of two parts. In first, Multilayer Cluster Designing Algorithm for life time improvement of WSN is discussed in detail. Background of targeted problem is discussed proceeded by set assumptions and definitions for the proposed solution. Various aspects of MCDA are discussed in detail with pseudo code. Comparative analysis of MCDA with contemporary solutions is conversed in detail. Second part discusses the extension of proposed solution i.e. MCDA given in the first part with the name Extended-MCDA. Proposed Idea is splendid with novel algorithms for time slot allocation, minimizing the cluster head competition candidates, and cluster member selection to cluster head play underpinning roles to achieve the target of ameliorating the performance in WSN's life time. Substantial simulation based results are demonstrated with sufficient discussion thereon intuits the outperformance of E-MCDA compared to state-of-the-art solutions.

- Chapter 5 addresses the second and third research questions of underlying dissertation. The proposed Energy aware routing mechanism for WSNs is presented projecting the highlights of MCDA for energy aware routing followed by the Energy Efficient Cluster Head Rotation Technique. Complete energy efficient routing process is given in particularized at the end of proposed solution section. Empirical results on the proposed solution with competitive algorithms is demonstrated in detail to claim of energy aware network architecture for Homogenous Wireless Sensor Networks aggregately.

- Chapter 6 concludes the dissertation by highlighting the important aspects that have played their indispensable roles in proving the claim and in addressing the research questions successfully. Possible future directions in the mentioned networks have also been discussed in this chapter.

Chapter 2

2 Analysis of Energy Aware Routing

Routing is the process of selecting paths in the network along which to send network traffic destined to certain destination by using certain routing algorithm.

Node sends packet to its neighboring node(s) which is closer to the destination. This packet is further passed on to the node(s) closer to the destination. This passing on process, which is called forwarding, continues and ultimately the packet reaches the destination. There may exist one-to-many or many-to-one or many-to-many relationship between source and destination. Due to which routing may follow static path or dynamic path as well as can be Unipath or Multipath depending on the designed algorithm and required application. In their delivery semantics, routing schemes differ to form following four types (Figure 2.1).

- **Unicast**: transmit the packet to a single specified node.
- **Broadcast**: transmit the packet to all nodes in the radio range.
- **Multicast**: transmit the packet to a specified group of interested nodes.
- **Anycast**: transmit the packet to any one nearest to the source out of a group of nodes.

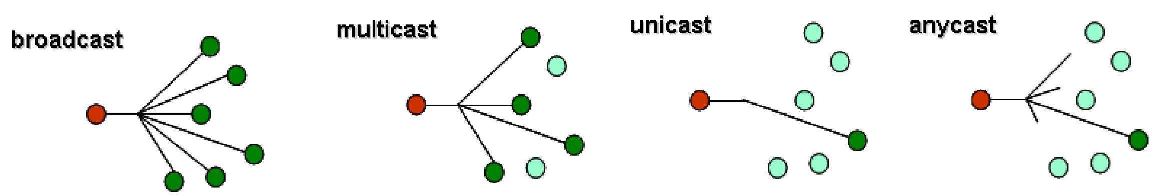


Figure 2.1: Routing Schemes

Usage of routing scheme is requirement specific. At the network layer, the designed protocols for the routing process need to be carefully designed at many aspects to conserve energy. Taking care of energy consumption in its functionalities from communicating the data to a neighboring node to choice of communication style, and from forwarding node selection to approaching the data to BS is called energy aware routing.

2.1 Factors Affecting Energy Aware Routing

In this chapter, the under consideration topic is related to network layer for analyzing the factors whose affect is most on the energy aware aspect of the routing process along with a graphical representation for a better comprehension. This is discussed in subsequent paragraphs.

2.1.1 Broadcasting

Broadcasting is the process of communicating a message to the nodes in foot print in one transmission. It means that the transmission of a node (N_i) is received by all the nodes ($\mathrm{N_j}$) in the radio range of i^{th} node (r_i). By referring to Figure 2.2, It can be represented as: $\left|\mathrm{D}\left(\mathrm{N_i}-\mathrm{N_j}\right)\right| \leq \mathrm{r_i} \quad \forall_{\mathrm{j}}$ Where $\mathrm{j}=1,2,\dots 6$ and $\mathrm{D}\left(\mathrm{N_i}-\mathrm{N_j}\right)$ is distance between N_i and N_j. The neighborhood range can be increased or decreased with dynamic power adjustment i.e. increasing or decreasing the communication power [99]. In other words, the number of neighborhood nodes is the increasing function of transmission power. Although in wireless networks this categorization of routing schemes as broadcast, unicast, multicast or any cast is set at the recipient level with respect to its targeted listeners, yet all the neighbors receive the transmission under the promiscuous receive mode. So the communication is always broadcast but decoding of the packet is only done by the node(s) whose address (es) is/are encapsulated in the packet at recipient field. This makes the transmission broadcast, unicast, multicast and anycast. Figure 2.1 depicts aforementioned routing schemes [100].

In most of the jobs during routing process, neighbor information is collected through probe messages (a beacon message to simply see whether the destination actually exists) to know the nodes' status (alive or dead) and to communicate nodes' parameters (energy, memory, nodes' id) [101]. Piggybacking is a very common technique for updating the neighbor node about node status or query some neighbor node by exploiting the control packet. This can also be broadcast, unicast, multicast or anycast. Due to these very reasons of "*always broadcast nature*" of messaging in wireless communication, broadcasting / beacon messages are being discouraged until unless direly needed. These create congestion, increase end to end delay, affect the routing and hence the network efficiency. Apart from it, these also consume much energy in receiving, demodulating, de- capsulating, and related processing [70].

Although broadcasting is the severe rivalry of energy aware routing yet, it is the vital part of most of the routing features like, cluster formation, cluster head election, cluster head rotation, path establishment, forwarding node selection, setting up a neighbor table and routing table, path maintenance, etc. Due to its core importance in these functionalities, a number of different ideas are floated, and solutions are proposed to minimize message broadcasting [102] and beacon message exchange [103]. A routing algorithm with minimum broadcast in the stringent constraint energy factor environment is appreciated in the research community. The straightforward approach of broadcast to establish the route is blind flooding [104]. In which each node is obligated to re-broadcast the packet whenever it receives a packet for the first time. Blind flooding generates many redundant transmissions. These redundant transmissions may cause a serious problem, referred as the broadcast storm problem [105] [106], in which redundant packets cause contention and congestion. A common approach for the remedy of broadcast storm problem is packet sequencing. When a node has packets to broadcast in the network, the broadcast protocol should route these packets to all nodes in the network with little overhead, latency, and consumed energy.

Graphical representation of this process is given in Figure 2.2.

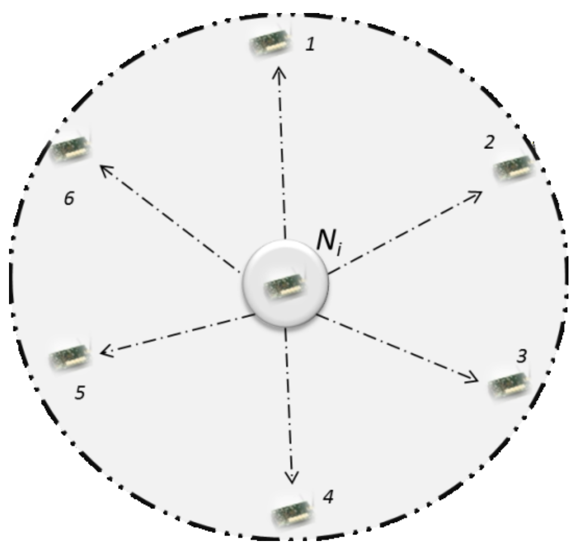


Figure 2.2: Broadcasting Process

2.1.2 Forwarding Node Selection

The node that makes the way for a node to communicate its packet to other nodes in a network or to the base station is called forwarding node and the process of finding such node is referred to as forwarding node selection. According to Jie Wu *et al.* [107], in a broadcast process, the source and a subset of nodes form a flood tree such that any other node in the network is adjacent to a node in the tree. Nodes on the tree are called forward nodes and form a Connected Dominating Set. Forwarding node must be in the foot print of the current node. Forwarding node selection is the key step in route discovery, re-route discovery, loop free routing and void bridging. For these to complete, the efficiency of any routing protocol depends mostly on the selection of node that may lead its data to the destination. In the case of clustered network architecture, forwarding node for a Cluster Member (CM) node can be CH or other CM node and then the CH, depending upon the communication scenario. The selection parameter can be energy, distance to destination, nodal density (node degree), and feasible position, time to reach BS, hop count to BS or the combination of any among these. So, a sensible decision for selecting the most suitable node for forwarding the message or data to the targeted destination node matters a lot in the success of any routing application. Its importance gets more priority when there is concern of real-time application. In view of all its importance, proper resources are allocated to select an effective and accurate forwarding node that ultimately results in more energy consumption. It makes the routing protocol less energy efficient. The selection parameters for forwarding node varies with the intended application but in all cases, energy conservation is and should be considered, since energy is the stringent constraint factor in WSN. More-over, a better tradeoff is also required among the competing selection parameters [108]. For example, in real time application energy, time and distance to destination (BS) are the competing factors [109]. Jie Wu *et al.* [107] target the combined effect of broadcasting and forwarding node in designing the protocols for networks with scarce resources. Ad Hoc and WSN can be the examples for such networks. The taxonomy of broadcast routing protocols and nature of algorithms is also discussed.

Let there is a node $'M'$ in the deployed network. All the nodes (N_j) which are in the foot print (r_m) of node M are assumed to constitute the forwarding candidate neighbor set (FS).

If the distance to base station $D(B_S)$ is the selection criteria for forwarding node then the node *(N_j)* which has the least distance to base station will be the most favorite for being selected as forwarding node. It can also be represented as follows:

$$|D(M - N_j)| \leq r_m \qquad \forall_j \qquad Where \quad j = 1,2, \dots 6$$

$$|D(N_j - B_S)| \leq |D(N_k - B_S)| \qquad \forall_k \quad Where \;\; k = 1,2, \dots 6 \quad and \quad j \neq k$$

Figure 2.3 demonstrates this process graphically.

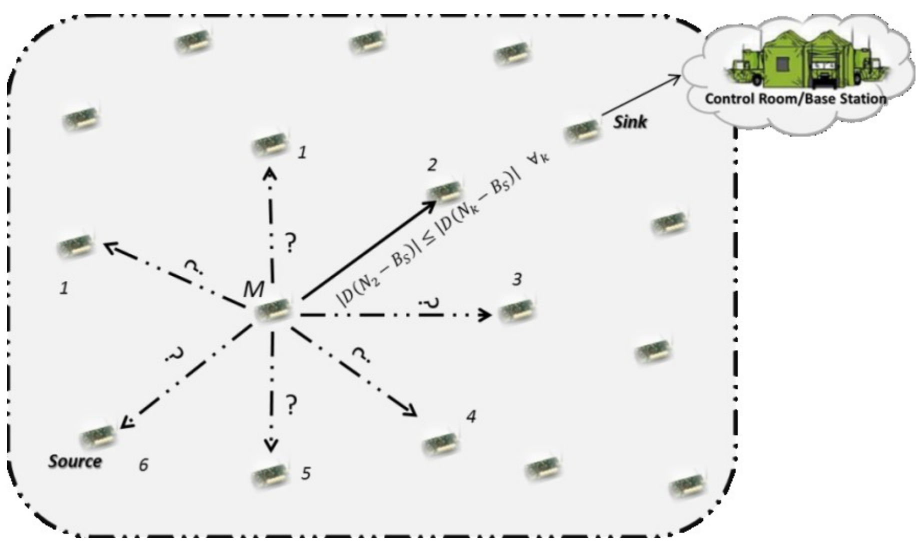


Figure 2.3: Forwarding Node Selection Process / Route Discovery Process

2.1.3 Route Discovery

The ultimate purpose of any routing protocol in WSNs is to bring the sensed or generated data from the source node to the sink node. In some cases, usually in a small flat network, this data is directly sent to BS, so no case of route discovery at all. In the scenario of cluster based architecture, the sensed data is communicated either directly [110] or through multi-hop to the CH [98] which is further sent either directly to the BS [91] or through multihop [110]. In the other case that is most prevailing in large scale flat and cluster based WSNs due to the limitation of communication range of node, the data is transmitted from source to sink through transient nodes (forwarding node). The better selections of these transient nodes accumulate to a better route to the base station. Less energy consumption, minimum end-to-end delay, minimum path length (hop count or distance), less number of transient nodes, better value for performance metric calculation or combination of these, are the common characteristics of a favorable and effective route [111] [112] [113]. Priority level of these characteristics varies with targeted application. Some can be compromised on cost of others. As an example, in real-time application, end-to-end delay has the highest priority, and it must be achieved even to the cost of energy. In the competing factors, tradeoff should be set at some breakeven points. For example, among three paths, *P1, P2* and *P3*, from source node, So to the destination node *Do, P1* has less number of transient nodes (N_t) but it is lengthy (P_L). *P2* has more number of transient nodes with lesser length from source So to the destination Do i.e. as compared to *P1. P3* has a number of transient nodes and path length that is average of both path P1 and path P2. i.e. $N_t(P_1) < N_t(P_3) < N_t(P_2)$ $and \;\; P_L(P_2) < P_L(P_3) < P_L(P_1)$.

Hence, Path P_3 has the characteristics that are at the tradeoff. So, it should be selected to route the data. The route discovery process is modeled in the same way as that of forwarding node selection. Figure 2.3 demonstrates this process graphically.

2.1.4 Re-Route Discovery

An extension of route discovery process is re-route discovery. Death or malfunctioning of nodes may result in breaking of the established path and may lead to network partitioning. So the need arises to discover a new path. This path setting up phase that is initiated due to the breaking of the established path is called as re-route discovery. This process is almost same as that of route discovery that has been discussed a short before just with a difference of initiating cause. More-over, forwarding node selection is also an inseparable part of route discovery process. Death of node can be identified by the following methods:

1. If for a specific time period 't', no reply of query packet is received from the relay node / forwarding node then it may be assumed that no more existence of this node.
2. If for a specific time period $'t'$ transmission acknowledgement from the destined node is not received then it may be considered dead.
3. In an established path, if the expected message is not received from a specific node for a defined time and for defined repeated requests then node may be either considered being trapped or dead.

So in such situations, re-route discovery process is initiated to re-establish the disconnected path. This rout failure remedy is more frequently needed in Mobile Ad Hoc Network [114] as compared to Static Ad Hoc Network [113].

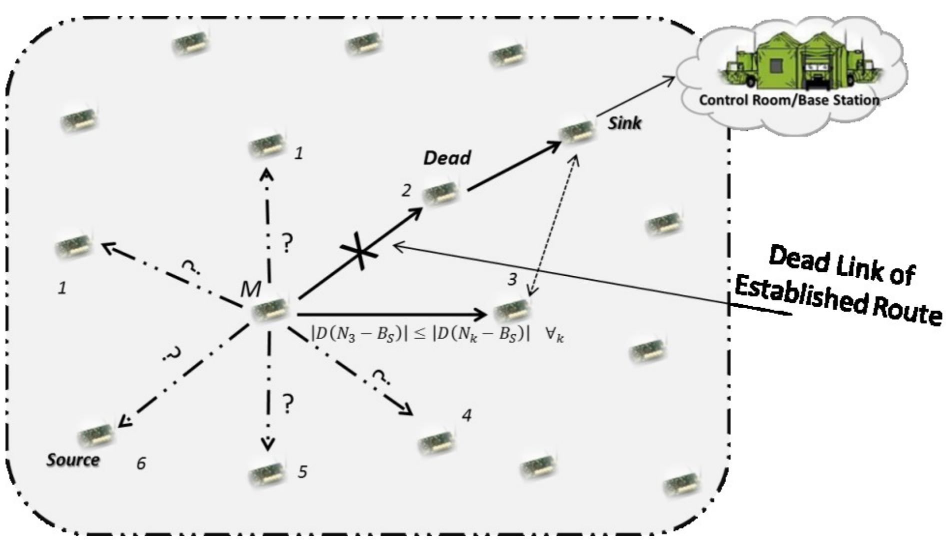


Figure 2.4: Re-route Discovery Process

Let there is a node $'M'$ in the deployed network. All the nodes *(N_j)* which are in the foot print *(r_m)* of node $'M'$ are assumed to constitute the FS. If the distance to base station $D(B_S)$ is the selection criteria for forwarding node then the node *(N_j)* which has the least distance to base station will be the most favorite for being selected as forwarding node except N_2 that is already dead and due to which the re-route discovery process is initiated. This re-route discovery process can also be represented as follows:

$$\left|D\left(M - N_j\right)\right| \leq r_m \qquad \forall_j \qquad Where \qquad j = 1,2,\dots 6$$

$$\left|D\left(N_j - B_S\right)\right| \leq \left|D(N_k - B_S)\right| \quad \forall_k \quad but \quad j \neq 2 \quad Where \quad k = 1,3,4,5,6$$

$$and \quad j \neq k$$

Figure 2.4 demonstrates this process graphically.

A special case of re-route discovery arises

i. When the established path is disconnected due to the death of forwarding node.
ii. When among the neighboring nodes, distance to the destination is more than the current node's distance to destination.

Then it creates a gap called void and may result in network partitioning (a scenario where a network is divided into two or more than two parts those ever were one). Finding a route to fill this gap is called a void bridging. More-over, Voids are also formed due to the random deployment of the nodes that raises the aforementioned second issue.

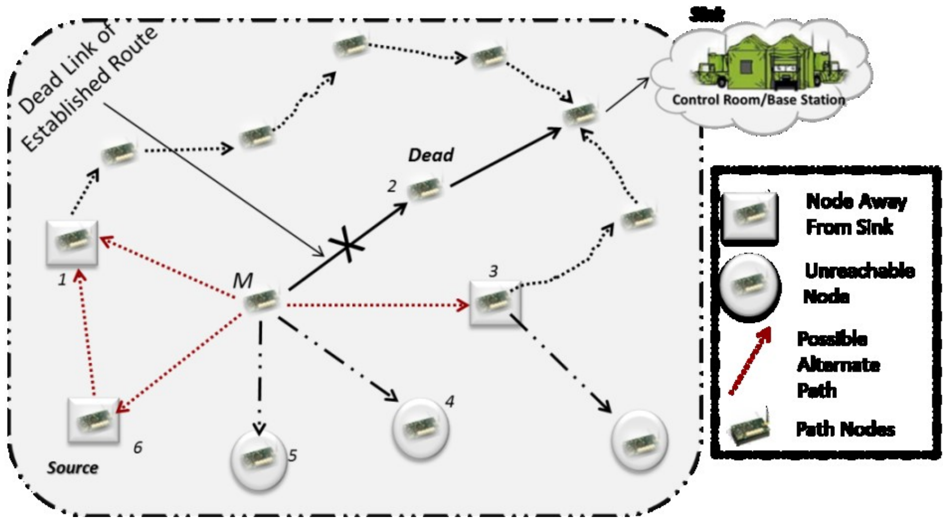


Figure 2.5: Void Bridging Process

In Figure 2.5 the forwarding node ‘*2*’ in the path from node $'M'$ to sink has gone dead that was the only node in the FS of node$'M'$. So, node $'M'$ is stuck since it has no neighbor that is so close to be selected as the forwarding node because its FS is empty. Hence, no data can be positively progressed to the sink from this node. To bypass this situation (void), packet is forwarded in a negative progression using the local minimum phenomenon [115]. Let node ‘3’ in Figure 2.5 is selected even it is away from sink and not from the FS to lead the packet towards sink. So, the appropriate void handling approach is important both in flat and clustered network to save the node’s resources (energy, computation) as well as the communication or packet to be lost. Such behavior is direly discouraged in the time-critical applications since network mission can be severely affected by the loss of some captured information [116]. This can be bridged by right hand rule [117] or by back tracking the path and find the route to destination by linking with some other established path [118] or by establishing a complete new path. Same process is followed to established new route as is for route discovery or re-route discovery. In such scenarios, Multi-path to destination is a feasible technique. But it has its own dis-advantages due to multipath finding and managing. Although the route found in such a way of back tracking is lengthy and can be infeasible, yet it saves the data to be lost continually and the network from partitioning.

2.1.5 Neighbor Table and Routing Table

The nodes that come within the foot print of the node $'M'$ are considered its neighbors and the format in which and where the information of these neighboring nodes is kept in the node *'M'* is called neighbor table. Its size is increasing function of number of neighboring nodes which is further directly proportional to the transmission power [119]. In the dense network (where the number of nodes per unit area are more than usual or in other words where the distance between nodes is far less than usual), its size is bigger as compared to the sparse network [120] (where the number of nodes per unit area are less than usual or in other words where the distance between nodes is far more than usual). In memory constraint environment, such as that of WSN, keeping the information of all the neighbor nodes is a bit challenging task especially when the deployment is dense. So, different strategies are adapted as given below:

1. A threshold value of parameter (energy, memory, node density, work load, or queue size etc.) is defined and the neighboring nodes whose values meet to that defined threshold criteria are kept in the neighbor table [111].
2. Among all the nodes in the neighbor that have the redundant data, only one node's information is added in the neighbor table [121].

Many routing algorithms need neighbor table of the current node [111] and of the neighboring nodes as a pre-requisite to start functionality or to complete their task.

Adopting the same strategies as enumerated before help in energy conservation due to less size. This requires neighbor table, (i) to be updated, (ii) to be communicated, and (iii) to be stored in one case or the other. Each of these three requirements has their separate challenges to be satisfied and have their optimistic or pessimistic contributions in different routing algorithms designed for various applications. More-over, they may directly or indirectly result in (i) Network congestion, (ii) Increased packet drop ratio, (iii) Increased end-to-end delay, (iv) Increased packet size, (v) Increased computation, (vi) Decreased throughput and the most important are (vii), more energy consumption, (viii) and decreased network life time. So, well-planned routing algorithm in this context is indispensable for successful energy aware routing protocol for WSN.

Let a node $'M'$ in the deployed network and a neighbor table $'Y'$ at node $'M'$ which contains all the nodes whose distance is less than the radio range of node $'M'$. So in the Figure 2.6 neighbor table contains the information of Node id ($N_{j_{id}}$) and Node's distance ($N_{j_{Dist}}$) from node $'M'$. This can be represented as follows:

$$\exists_{\mathrm{M}}\ \exists_{\mathrm{Y}}\quad \mathrm{M} = \text{ Node and Y} = \text{Neighbors of M in the neighbor table}$$

$$\mathrm{At}(\mathrm{M} : \mathrm{Y}) \quad \wedge \quad \mathrm{N_j} \in \mathrm{Y} \quad \text{and} \quad |\mathrm{D}(\mathrm{M} - \mathrm{N_j})| \leq \mathrm{r} \quad \forall_{\mathrm{j}} \quad \text{Where} \qquad \mathrm{j} = 1, 3, 6, 13$$

$$\text{and} \quad \mathrm{N_j} \ni (\mathrm{N_{j_{id}}}, \mathrm{N_{j_{Dist}}})$$

The participating nodes that assist a packet to move to the destination node make the route. Those constituent nodes of the routing path are called as the route nodes. The table that keeps track of those route nodes in a specific format from the current node to the destination node (Sink Node) is called as the routing table. The table may contain various attributes of route nodes from node id, node energy level, congestion rate, packet drop ratio, memory and distance from sink depending on the routing algorithm, target application or decision requirements [122] [123].

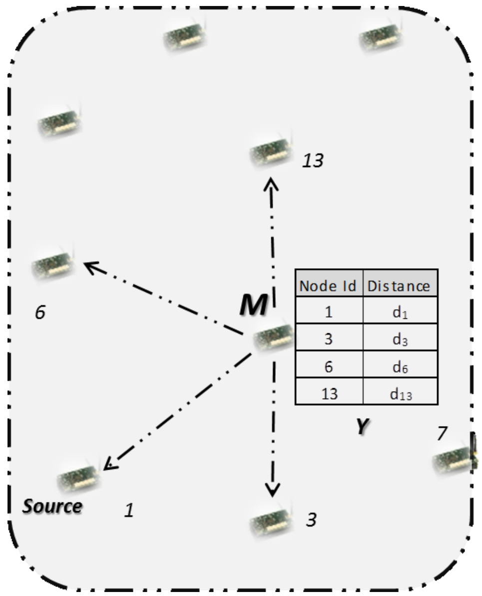


Figure 2.6: Neighbor Table Designing Process

In some of the cases, routing table needs to be communicated but its regular update is necessary in almost all cases. Memory constraint is also a factor that is to consider in managing this aspect of routing. These all have their strong impact not only on the efficient routing positively but also on its energy consumption aspect negatively. This severity becomes more intense in the case of large scale network. Hence, big routing table consumes more network energy along with pessimistically affect other network parameters. Since cluster based network is more organized than flat based sensor network. So, establishing and maintaining the updated routing table in clustered network is comparatively less costly than in flat networks. Due to these very reasons, exchange of the routing table is not appreciated to be a part of routing algorithm until unless direly needed. This need can be the case of routing that is affiliated to the requirements of routing algorithm or underlying application. Introducing the routing table is more common in Static WSN as compared to Mobile WSN. Its management is a big challenging task and in some cases almost impossible as in the scenario with high mobility of nodes. Routing table designing strategies, its requirements, and its challenges are almost same as that of the neighbor table mentioned previously in the same section with some tailoring effects.

Let in a network of n nodes, X and Y are source and destination nodes and i and j are intermediate nodes with node id's *7, 25, 12,* and *14* respectively. Routing table R at node X has the information of complete path P that comprises of links (→) from source node to destination node passing through the intermediate nodes in such a ways that each next node, say i is in the radio range r of previous node, say. This is represented as $|D(X-i)| \leq r$. A simple representation of this scenario is given below.

$\exists_X, \exists_{Y,} \exists_R \qquad X = Source\ Node \quad and \quad Y = Destination\ Node\ and\ R =$

$Routing\ Table$

$At(X : R)$

$\exists_i\ \exists_j \qquad i,\ j = Intermediate\ Nodes$

$Where \qquad |D(X-BS)| < |D(i\ -BS)| < |D(j-BS)| < |D(Y-BS)|$

$In\ addition,\ L_1 = X \ \rightarrow i\ , L_2 = i \rightarrow j, L_3 = j \rightarrow Y$

$R = \ L_1 + L_2 + L_3$

$and\ \ |D(X-i)| \leq r_X\ , |D(i-j)| \leq r_i\ , |D(j-Y)| \leq r_j$

Same is depicted in Figure 2.7.

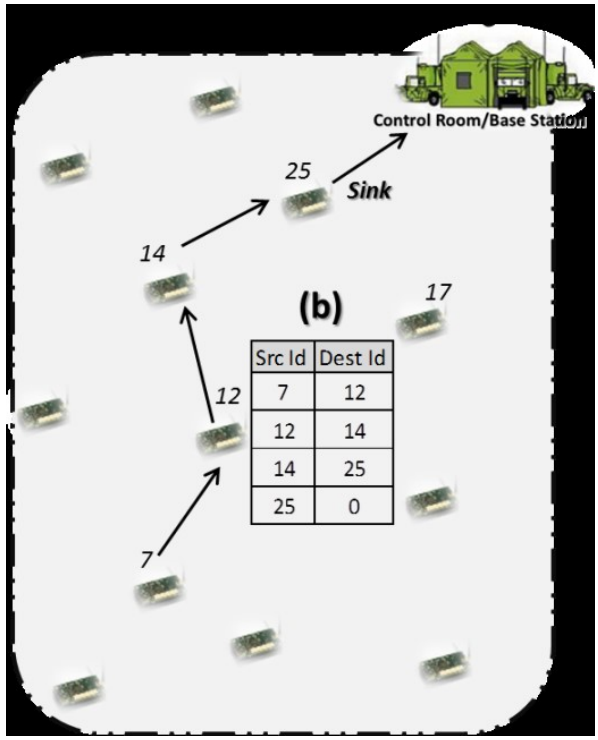


Figure 2.7: Routing Table Designing Process

2.1.6 Network Clustering

Grouping of autonomous nodes in a centralized way to designate one node as head and other nodes as members is called clustering. Group is named cluster. Designated head is termed as cluster head, and the member nodes are called as a cluster member. A node that is still not the part of any cluster is an undecided node. Cluster head acquires the sensed data from cluster member nodes, aggregates and forwards it to other cluster heads directly or via some transient node or gateway node (multi-hop) or directly (direct-hop) to the base station. Hence, in clustered network architecture, nodes are designated at different roles.

The routing process in clustering is split into intra-cluster (within the cluster – cluster members nodes to the cluster head) and inter-cluster (between clusters – from CH of one cluster to CH of another cluster) data transmission. This data communication style leads to significant energy saving. If all the nodes in the network are of same configuration (energy, computation power, memory etc.) they are called as homogenous nodes [124] and in case of different configuration, they are termed as heterogeneous nodes [125]. The process of designating a node in the deployed network as a cluster head i.e. CH selection is usually the initial phase in the designing of clustered network. While establishing the route for communicating the sensed or received data from the deployed nodes is usually its last phase [110]. Figure 2.8 demonstrates these steps that are involved in the constitution of clustered network.

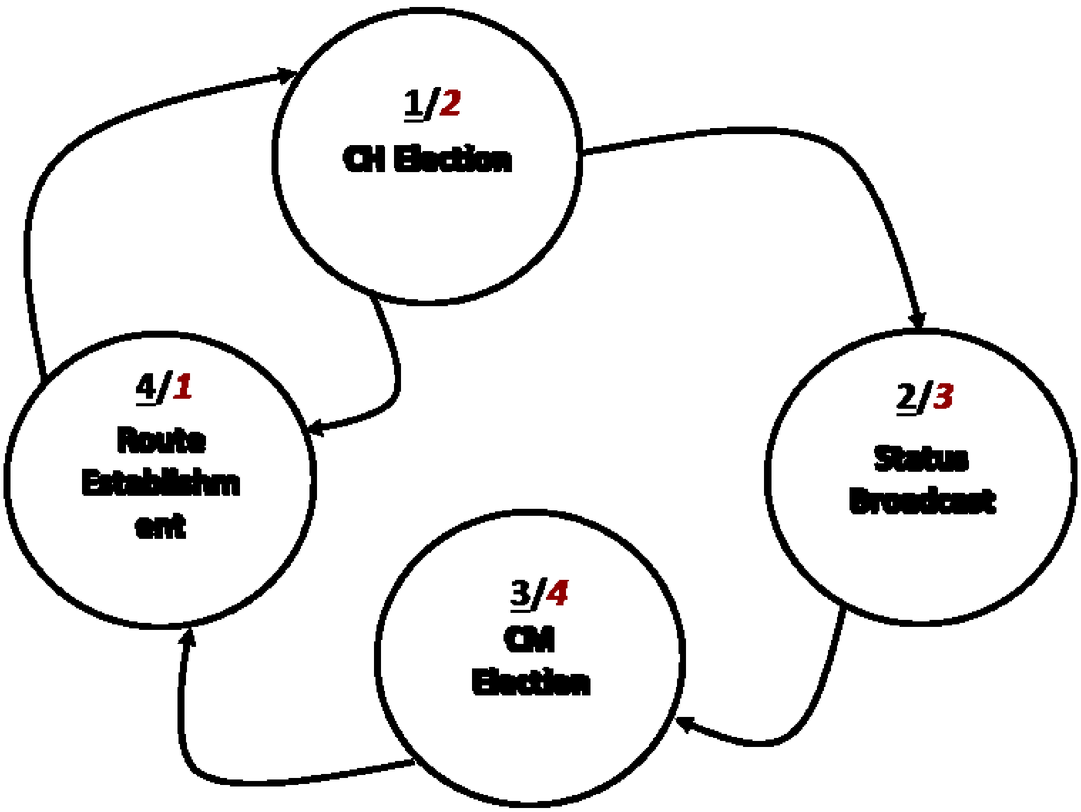


Figure 2.8: Steps in Constitution of Clustered Network – Numeric Values in underline is one sequence of steps and in italic is other sequence of steps

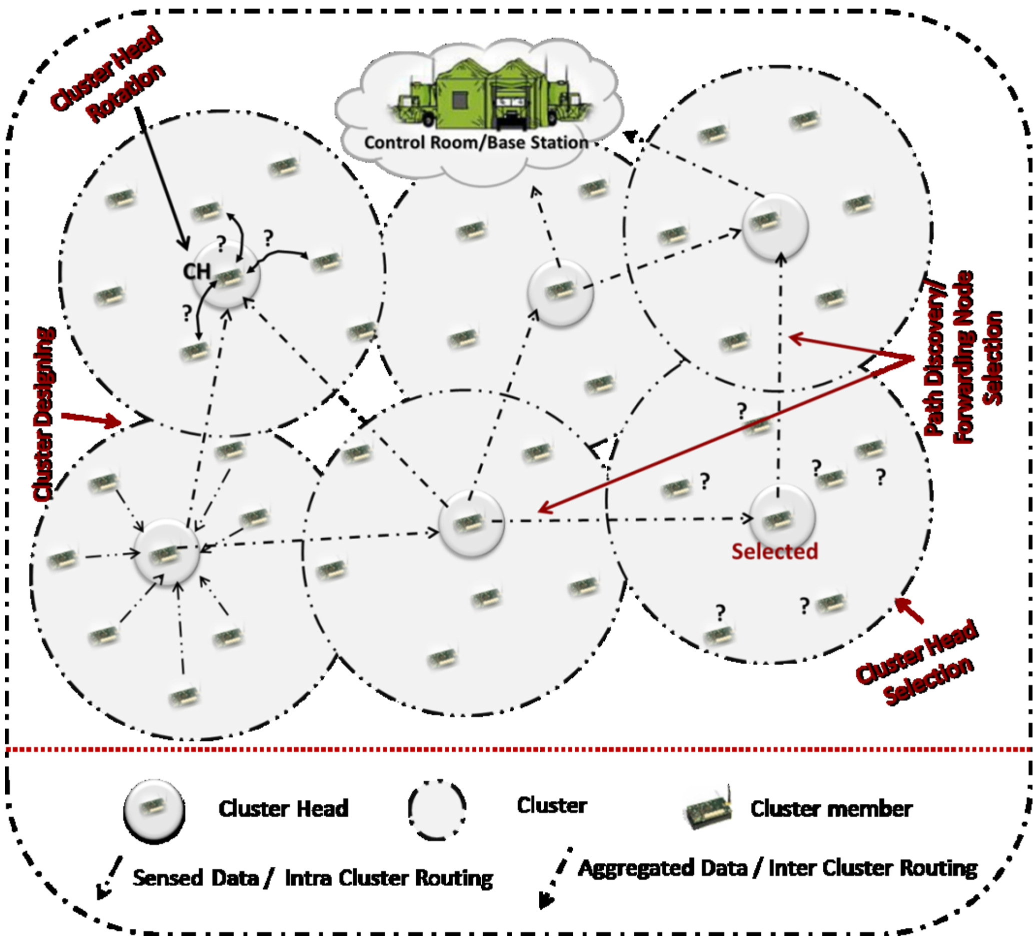


Figure 2.9: Complete Scenario of Clustered Network Architecture

The architectural setup of clustered network has self-support in the conservation of energy. In such type of networks, a high energy and appropriately positioned cluster head that acts as a gateway, plays a vital role in solving the said problem [126]. Clustered network is considered to be the most energy efficient architecture due to its ease in route discovery, fault tolerance, data aggregation and shortest possible end-to-end delay nature [127]. Although cluster based network is a proven architecture for energy aware routing yet, more attention is required to ameliorate the energy consumption aspect of its cluster designing process. Figure 2.9 portrays the key constituents and processes of clustered network architecture in WSN.

2.2 Summary

As concluding words from the above-detailed discussion, WSN technology has woven itself in a diverse fabric of applications due to its capabilities for involvement in multi-disciplinary research and its nourishing from well-renowned group of researchers and organizations. Digging its multi-facet capabilities for efficient performance has also unfolded variety of issues as its by-product and hence it has a long list of hot issues to attract researchers' mind to fix those as is elucidated in Figure 2.9. Among those, the most common is memory, computation issues and the most important is energy constraint. Sensing, transmitting and receiving are the most energies squeezing functions in the processes of sensor nodes among which transmission is the most energy draining function. These constitute a routing phenomenon to communicate or to relay the sensed data destined to certain destination. Since the communication is wireless and mostly the deployment of nodes is random, so for a well-structured and energy efficient communication, various techniques and algorithms are devised and are presented in the literature. A well-planned survey of these techniques and algorithms with the name of factors affecting the energy aware routing is presented.

Hence, network layer functionalities are of core importance in the communication process and routing with energy aware trait is indispensable for improved network performance and increased network life time. Designing of protocol at network layer must consider the aforementioned factors especially for energy aware routing process. Two main types of network architectures for dissemination of sensed data from source to destination exist in the literature; Flat network architecture and Clustered network architecture. In WSN, there may be hundreds or thousands of sensor nodes communicating with each other and with the base station, which consume more energy in exchanging data and information with the additive issues of unbalanced load and intolerable faults. In flat architecture based networks, uniformity can be seen since all the network nodes work in the same mode and don't have any distinguished role [5]. So usually no conservation of energy is supported by itself from its architectural setup. Some of the well-known protocols for this network architecture are mentioned in [17] [128] [129]. The more optimized algorithms for designating the network nodes as cluster heads and cluster members, their inter-communication and CH role rotation have proven the priority of clustered network over the flat architecture based networks. Clustered network is considered to be the most energy efficient architecture due to its ease in route discovery, fault tolerance, data aggregation and shortest possible end-to-end delay nature [127]. According to Soroush *et al.* [130], clustering scheme shows significant advantages over flat strategies. They enumerated following advantages of clustering scheme that introduce it as the most compatible architecture with WSN's attributes:

- The imbalanced load over the deployed nodes is almost balanced with an equal size clusters and centralized management.
- Bandwidth constraint issue is resolved by efficiently reducing the bandwidth demand.
- The overhead for routing and topology maintenance is reduced due to centralized management.
- Data aggregation can be effectively used to eliminate redundant and highly correlated data.

- In the inter-cluster and Intra-cluster communication, the collision and interference can be reduced by the use of multi-power levels.
- The manageability and scalability of the network are improved.
- Routing table becomes too small due to localizing the route setup within the cluster boundaries.
- Overall transmission power is minimized.

Chapter 3

3 Related Work

This chapter encapsulates three layers of related work; Cluster designing, Cluster head selection and rotation, complete routing process (forwarding node selection, intra-cluster, inter-cluster routing etc.). In the subsequent subsections, these milestones of our literature survey are covered in detail with summarized view of each in descriptive or tabular format.

3.1 Cluster Designing

Among the cluster-based routing protocols for wireless sensor networks, LEACH [91] is designated as the pioneer protocol among these. Literature is rich with the variants of LEACH. Some of the improvements and ramifications of LEACH are given in [131] [86]. All these variants use almost the same technique of distributed cluster designing with very little improvement as in LEACH. The following Equation 1 that is used by LEACH protocol for cluster head election and cluster head rotation can be seen in literature with many improvements [131] [132] [133].

$$T_i(n) = \begin{cases} \frac{P}{1 - P \times \left(r \bmod \frac{1}{P}\right)}, & \text{if } n \epsilon\, G \\ 0, & \text{Otherwise} \end{cases} \quad (1)$$

$T_i(n)$ is the threshold value. P is the representation of cluster-head probability, r is the number of the current round and G represents the set of nodes that have not already been elected as the cluster head in the last *1/P* rounds. This equation ensures that within *1/P* rounds, every node in the deployed node set becomes the cluster head only once.

The said LEACH equation is modified with various parameters like energy [132], distance from the base station [132] or with the introduction of some routing techniques to replace the existing routing process of LEACH. Furthermore, some additional efforts are undertaken to extend its scalability such as introducing vice cluster head [93] or primary and secondary cluster heads [96]. Following is the description of some of the famous aforementioned protocols.

To decrease the energy consumption in clustered-based wireless sensor networks, Yassein *et al.* [93] have introduced an improved version of LEACH where CH was only involved in the process of sending data, which were received by other clusters. This stingy involvement saves a reasonable amount of energy compared to LEACH due to replacement of direct hop with multi-hop. For any process to be successful, it is important to have a backup plan. A similar approach is adapted in this improved version. Due to the heavy load on CH, there is a possibility of the crash or the CH may die before the expected time. To avoid such a situation, a vice CH is introduced in [93] to take the responsibilities of the main CH and protect the whole system from the chaotic situation. To increase the network life, the hierarchical clustering algorithm has its proven importance in the literature [92].

Meenakshi *et al.* [132] have proposed a level-based hierarchical clustered routing algorithm named EELBCRP: Energy-Efficient Level- Based Clustering Routing Protocol. This proposed algorithm increases the network life time by reducing the energy consumption that results in decreasing the number of dead nodes. This idea of dividing the network into levels also gave us the clue of multi-layer design of Wireless Sensor Network.

The authors have taken a network of *n* sensor nodes to form a clustered network. In this network, the nodes are randomly deployed. The authors make following assumptionss about the sensor nodes: the network comprises a fixed base station located in the middle of the deployed network along with fixed homogenous and limited energy-carrying sensor nodes. Dynamic power adjustment can be done so that the data reach the base station through the intermediate nodes. A level-1 signal is transmitted with a minimum power level by the BS after the deployment of the nodes. All the recipient nodes set their level as 1. In the second step, a level-2 signal is transmitted by the base station with an increased power level. Similarly, all the recipient nodes except the first level-1 nodes set their level as level-2. To cover all the deployed nodes, the base station continues to send a signal to define the levels up to boundary nodes at the opposite end of the base station and assign it to the corresponding level. Then the BS broadcasts a *hello* message containing the information of higher and lower limit, i.e., the upper limit (U_i) of level i and lower limit (L_i *of level i*) of each level. This helps the node to calculate its distance from the base station on the received signal strength. The Following formula in Eq. (2) i.e., the extension of LEACH cluster head election formula, is used for the same purpose and in the same way.

$$T_i(n) = \begin{cases} \frac{P}{1-P\times\left(r \bmod \frac{1}{p}\right)} \times \left(\frac{U_i-d(n,BS)}{U_i-L_i}\right) \times \left(\frac{E_{cur}(n)}{E_{ini}(n)}\right)^k, & \text{if } n\epsilon\ X \\ 0, & \text{Otherwise} \end{cases} \quad (2)$$

In Equation 2, $T_i(n)$ is the threshold value, $P$is the percentage of the required cluster heads. So, it is up to the network deployed team to define the maximum number of required cluster heads among the deployed nodes. r shows the current round, since each round defines one successful delivery of packet from source to destination. Second successful delivery of packet from the source to destination defines the second round and so on. C is the constant factor having value between 0 and 1. U_i and L_i represent the upper limit and the lower limit of level-i. $d(n, BS)$ means the distance between the node n and the base station $E_{cur}(n)$ current energy of node n, $E_{ini}(n)$ is the initial energy of node n and k is the value from 0 to 3. The authors have used the CSMA MAC protocol at the second layer, Medium Access Control layer. On electing the cluster head for the continuing round, all the cluster heads broadcast an advertisement message with the same transmission. The recipient nodes other than the cluster heads reply to that specific cluster head to which they are finalized to join as cluster member. On receiving the advertisement from more than one cluster head, the decision of the non-cluster head for joining the cluster head is then based on the received signal strength. It means, it sends a join message to that cluster head from which it receives a stronger signal strength.

M. Ye *et al.* [134] have proposed a new enhanced version of LEACH protocol with the name Energy-Efficient Extended LEACH (EEE LEACH) protocol. The basic idea is the same as of LEACH. This new version of LEACH protocol establishes multilevel clustering approach to minimize communication distance between nodes and introduces master cluster heads along with cluster heads. The proposed solution is based on the belief that the more the number of clusters increases, the more does the communication distance decrease and, as a result, the energy efficiency of the protocol increases. EEE LEACH outperforms simple LEACH protocol in MATLab based simulation by taking the energy consumption and effect of communication distance over energy consumption as the performance evaluation parameters.

Heinzelman *et al.* have introduced centralized cluster designing version of LEACH. [97] where the decision for cluster head selection and k optimal clusters is made at the base station. Almost all related protocols using CCD have the same basic strategy of decision making at the central point that is usually the base station with high energy level [135]. It decreases the distributed load of computation and message passing for acquiring the parameter values for that computation over deployed low-energy nodes as in BCDCP [86]. In the subsequent paragraphs, some of the algorithms available in the literature using Centralized Cluster Designing approach is presented. Centralized-Low Energy Adaptive Clustering Hierarchy (C-LEACH) [97] uses the same steady-state phase of the LEACH but introduces a centralized decision-making system for cluster head selection. Dispersing of the cluster heads throughout the network in C-LEACH gives better performance in terms of load balancing and energy consumption. The information regarding the current location (that is most probably determined by the GPS) and the node's energy level are communicated to the base station. To make clusters better in their size, it is ensured that the energy load is evenly distributed among the deployed nodes. The average node energy is calculated by the sink node, and the nodes having energy level below this average value are not assumed to take part in the cluster election process. Using the remaining nodes as possible cluster heads, the BS finds clusters by using a simulated annealing algorithm [136] to solve the NP-hard problem of finding k optimal clusters.

Almost the same style of cluster formation process is adopted in one of our publications i.e. "Threshold based Load Balancing Protocol for Energy-Efficient Routing (TLPER)" [17]. Deployed network nodes communicate information regarding their node density and geographical location to the BS.BS elects the node having the highest nodal density as the CH. BS communicates the decision to the network nodes. CHs broadcast their status of being CH. The non-cluster head nodes decide their membership based on the RSSI strength of CHs' status messages. Among the cluster members, the node with the highest energy level is set as the Assistant Cluster Head (ACH) to share the load of CH through Load Balance Threshold (LBT) technique and assists in energy-efficient CH rotation through the RTT technique. The simulation results are taken on overall network energy consumption and effect of load balance on the total number of packets entertained by vicinity heads and total network energy consumption.

Pu-Tai Yang *et al.* [137] have proposed a distributed re-clustering routing protocol: Predictive and Adaptive Routing Protocol using Energy Welfare (PARPEW). PARPEW incorporates the concept of energy welfare (EW) and tries to achieve both energy efficiency and energy balance simultaneously. At the beginning of each round, the base station starts the round and broadcasts the TDMA schedule to every node. The TDMA schedule specifies the time slots assigned to each live node to avoid packet collision in the cluster setup stage. PARPEW operates in each round in two stages: the cluster setup stage; and steady-state stage. In a cluster setup stage, clusters are formed, and CHs are selected. In the steady-state stage, sensors collect data and send it to their corresponding CHs. The CHs then aggregate the data and transfer it to the base station. First Cluster is formed then cluster head is designated.

Working of all this process is given in subsequent paragraphs.

1. p value (percentage of cluster head nodes)

2. αvalue *(an* inequality aversion parameter, which signifies the strength of society's penalty for inequality, and usually ranges from 1.5 to 2.5)

Each of the network nodes generates a random number between 0 and 1. If the generated random number is less than the p value then, the node elect itself as the temporal cluster head. Each selected temporal cluster head broadcasts its status. The recipient nodes join themselves to the closest temporal cluster head based on the signal strength. Each node of the cluster communicates its predictive residual energy after transmission (EAT) and its location information at least if the distance matrix is not available to the temporal cluster head. Using EAT and aversion parameter, Energy Welfare (EW) function is calculated for each of the cluster node. The node having the highest EW value is designated as the real CH. Assigning the time slots based on TDMA to the cluster members to communicate with real cluster head is performed by temporal cluster head.

Proposed Mechanism; Energy Aware Distributed Unequal Clustering (EADUC) by Yu *et al.* [138] is an energy aware routing algorithm for cluster based wireless sensor networks. They introduced unequal sized clusters for the remedy of hot spot issue that results in better network life time. Designing of clustering topology comprises of neighbor nodes information collection phase, cluster head competition phase and cluster formation phase that all constitute the setup phase. Each phase is given a specific duration i.e. T_1, T_2 and T_3. Next to it is the data transmission phase. To start the cluster formation process, the BS broadcasts a signal at a certain power level. Each node can compute its approximate distance to the BS based on the received signal strength. In first phase, each node broadcasts a *Node_Msg* message within its radio range r having node id and its residual energy E_r. Based on collected information, each node calculates average residual energy of its neighbor nodes. Next calculation is of waiting time t using the following formula given in Equation 3.

$$t = \begin{cases} \frac{E_a}{E_r} T_2 V_r, & E_r \geq E_a \\ T_2 V_r, & E_r < E_a \end{cases} \quad (3)$$

Where Vr is a real value randomly distributed in [0.9, 1] which is introduced to reduce the probability that two nodes send *Head_Msg*s at the same time. Each node waits until this calculated time prior to broadcast *Head_Msg* message.

To start cluster head selection competition phase, each node compares its average residual energy to its neighbor's calculated average residual energy and decide to be a cluster head or not. After waiting for calculated *t* time decision for the nodes to be a cluster, head is broadcasted with in their calculated radio range. If a node does not receive any *Head_Msg* message until the expiry of its time *t* then it broadcasts the *Head Msg* within radio range R_{C_i} to advertise that it will be a cluster head. Since the competition radius R_C determines the size of cluster that is based on the proximity to the BS. Each node calculates its own value for R_C using the following formula as given in Equation 4.

$$R_C = \left[1 - \alpha \frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}} - \beta\left(1 - \frac{E_r}{E_{max}}\right)\right] R_{max}, \quad (4)$$

where d_{max} and d_{min} are the maximum and minimum distances from the nodes in the network to the BS, $d(s_i, BS)$ is the distance from node s_i to the BS, α and β are weighted factors in [0,1]. This makes the cluster size bigger for farther elected cluster head and smaller for nearer elected cluster head. Each non-cluster-head node chooses the nearest cluster head and sends the *Join_Msg* which contains the *id* and residual energy of this node. Authors also modify this technique for heterogeneous networks by introducing energy factor in radio range competition radius in order to maximally exploit the higher energy nodes.

A very similar mechanism for energy efficient routing in clustered wireless sensor network and to target the hot spot issue is given in [139].Where Li *et al.* have proposed an Energy-Efficient Unequal Clustering (EEUC) mechanism for periodical data gathering applications in wireless sensor networks. It wisely organizes the network via unequal clustering and multi-hop routing. EEUC is a distributed competitive algorithm, where cluster heads are elected by localized competition. First Tentative Cluster Heads (TCHs) are selected with the predefined probability T. This style of selecting the cluster head is same as in LEACH where in the start all the deployed nodes are designated as cluster heads. Each tentative cluster head calculateR_{comp} i.e. competition Radius (a function of node's distance to the base station). Broadcast range of the tentative cluster heads to define their neighbor area of competition for becoming final cluster head is fixed by R_{comp}value. R_{comp} also dictates the cluster heads with higher residual energy and farther away from the BS to design larger cluster areas as compared to the CH closer to the BS which have smaller clusters. In order to complete the calculation for its maximum competition radius i.e. $S_i.R_{comp}$, each node must be communicated with the d_{max} (Maximum distance from the BS) and d_{min} (Minimum Distance from the BS) by the BS. Each tentative cluster head communicates its $Node_{id}$and RE (Residual Energy) value to its neighbor nodes. Thus each TCH prepare its neighbor set, S_{CH}. If the recipient node has the highest RE value among all the received values then it broadcast $FINAL\_HEAD\_MSG$ to propagate its status as Cluster Head. If it receives another $FINAL\_HEAD\_MSG$ from any other node from its neighbors then it just broadcast a $QUIT\_ELECTION\_MSG$. The non-cluster head nodes join the CH based on their closeness to it.

Table 3.1 shows the categorization of cluster-based routing protocols for wireless sensor network with respect to centralized and distributed cluster designing approaches. A more detailed analytical comparative discussion of these two categories of cluster designing approaches is discussed in next chapter backing with detailed simulation results.

Table 3.1: Categorization of Cluster based Routing Protocols for WSN

	LEACH [91]	EEE-LEACH [140]	V-LEACH [93]	C-LEACH [97]	TLPER [101]	EELBCRP [132]	BCDCP [86]	IMPERIA [141]	TL-LEACH [96]
DCD	√	√	√	-	-	√	-	-	√
CCD	-	-	-	√	√	-	√	√	-

3.1.1 Summary

The general trend in cluster designing scene is either centralized decision at base station for cluster head selection and its members called centralized cluster designing [86] or distributed decision by exchanging information between neighboring nodes until cluster head and its members are selected called distributed cluster designing [110]. Both the techniques drastically create mess in energy consumption due to too much broadcasting especially in large networks as well as message exchange until some final decision is made. As discussed in detail in section 2.1.1, broadcasting is one of the major factors that squeezes the node's energy. This needs to be considered and should be minimized at each functional level i.e. forwarding node selection to neighbor table or routing table, from cluster designing to cluster head selection and cluster head rotation and from aggregation process to routing process.

Though the available literature is rich with high quality articles on energy aware cluster designing as are cited in section 3.1, yet they seem to be lacking in covering key aspects to handle the factors that are discussed in section 2.1 i.e. Factors Affecting Energy Aware Routing. P. T. Yang et al. [137] require either GPS equipped sensors or some non-GPS technique to complete the working of their proposed solution. Former method increases the cost while in later case, algorithms to correctly identify the node's location are to be implied. That is an extra overhead to face. Same is the case with the idea proposed by C. Li et al. [139], J. Yu et al. [138], and Z. Yu *et al*. [142]. Some proposed solutions have formula with parameters like neighbor nodes' distance to BS, their energy, their nodal density, etc. that need intensive message exchange for collecting related information. The proposed solutions by M. Aslam et al. [143], G. Chen *et al.* [144], Z. Yu *et al*. [142] and C. Li *et al.* [139] follow the same fashion to a complete cluster designing.

K. Lee *et al.* [110] adopts distributed cluster designing approach in their proposed solution; A Self-Organized and Smart-Adaptive Clustering and Routing Approach for Wireless Sensor Networks (SOSAC). The involved fitness function in the solution requires information of node degree and node energy locally (one hop distance) and out of its local area. Rich message exchange is the inseparable part of this information collection process. Another node's energy draining factor is centralized calculation and decision making. The proposed solutions in [139], [137], and [144] are its typical examples. The proposed solution; An Energy-Efficient Unequal Clustering Mechanism for Wireless Sensor Networks (EEUC) by C. Li *et al.* [139] requires that each node must have the value for maximum distance and minimum distance of node from BS among all other nodes. These values are the pre-requisites to complete the calculation for identifying the maximum competition radius. On considering the worst case of this scenario, it has all the drawbacks related to the centralized cluster designing in large scale networks i.e. re-broadcasting of received broadcast from the far distant node to communicate their info to the BS. BS then broadcasts the extracted info of maximum distance and minimum distance from the received information.

Hence based on the comprehensive discussion on the network clustering techniques in section 3.1 and later a brief critical analysis thereon in this continuing section, the debate is concluded to have the need of an energy efficient cluster designing algorithm. This energy efficient solution must address all the aforementioned shortcomings in existing related ideas. More-over, we believe that a hybrid solution exploiting the pros of distributed and centralized cluster designing approaches and escaping the cons of these both techniques is highly appreciable to ameliorate the over network performance. It also must eradicate the cause of relatively high energy consumption during the cluster designing process.

Our novel layer based hybrid algorithm for cluster head and cluster member selection come up to novel communication architecture. Since its substantial constituent is cluster designing, so it is named as MCDA. Proposed design not only has its effect in lessening the blind broadcasting but also decreasing the message exchange. Furthermore, decisions are made locally, so minimize the message exchange. This energy saving endeavor is further backed by non-location aware idea and localized parameter encompassing calculations for cluster head and cluster member decision making. Proposed solution also encapsulates the beauty of efficient centralized decision-making i.e. one hop for various aspects of cluster designing and energy aware distributed cluster head selection and Cluster member allocation process. A constructive ramification of cluster designing mechanism floated in MCDA is also given in section 4.6. Novel algorithms for time slot allocation, minimizing the cluster head completion candidates, and node affiliation to cluster the head play underpinning roles to achieve the target. These incorporations in MCDA result in minimizing transmissions, suppressing unfavorable response of transmissions and near equal size and equal load clusters.

3.2 Completion and Maintenance of Clustered Network Setup

For the completion of clustered network setup, CHs and CMs selection are indispensable parts. Hence, after the initial step of cluster formation, the most appropriate node with respect to selection criteria is elected as CH to control the functionalities of cluster. CH manages the time slot assignment to CMs, routing the received data from member nodes towards BS, aggregating the acquired data etc. To get maximum benefits from CH, its selection is made carefully, and special algorithms are proposed for gaining the said benefits from its key position. In literature, different attributes of node such as its energy, degree, position, distance from BS and composite of any among these are used as major parameters for the selection of CH in initial round (right after or during the cluster designing process) and in subsequent rounds for maining the stability and longer life of network (CH rotation). In the subsequent sub sections, selection criteria for choosing CH and its rotation and for choosing CMs is summarized.

3.2.1 Cluster Head Selection

Initial round which is referred to the whole tenure that starts when a node is designated as CH right after or during the cluster designing process and ends when the performance optimality of this CH turns to non-optimality. In this sub section, we have presented an abstract view of commonly used techniques for the election of CH in the initial round.

In case of homogenous network where all the network nodes are of same configuration and so the energy of the nodes, selection of CH based on highest energy level among its members does not make much sense though energy is utilized during the cluster designing process and is consumed substantially, yet it is almost same for all the nodes and have less energy delta (ΔE) [131] [145]. In contrast to this, in heterogeneous network where nodes are of different configuration, following selection criteria work well.

- The energy E of a node N_i is higher than the individual energy E of all nodes N_j whose difference in distance from N_i i.e. $D(N_i - N_j)$ is less than its communication radius r_i

$$E_{N_i} > E_{N_j} \quad \forall_j \quad and \quad \left|D(N_i - N_{j)}\right| \leq r_i \quad \forall_j \quad Where \quad j = 1,2, \dots, n$$

This type of selection criteria is used in [137].

- In uniform deployment of nodes, node density as a selection criterion for CH does not work. However, in case of random deployment of homogenous as well as heterogeneous nodes, following the technique exploiting the nodal density works well.

  The density of a node D_{N_i} is higher than the individual density of all nodes D_{N_j} whose difference in distance from N_i i.e. $D(N_i - N_{j)}$ is less than its communication radius r_i.

$$D_{N_i} > D_{N_j} \quad \forall_j \quad and \quad \left|D(N_i - N_{j)}\right| \leq r_i \quad \forall_j \quad Where \quad j = 1,2, \dots, n$$

This type of selection criteria is used in [79] [146].

- The distance D between node N_i and Base Station BS is greater than the distance D between neighboring nodes N_j and Base Station BS. A node N_j is said to be the neighbor of N_i if it is in its communication radius r_i. This closeness of node is usually the determined by (i) No. of hops from BS, and (ii) Received Signal Strength Indicator (RSSI) from the beacon message from BS.

$$|D(N_i - BS)| \leq |D(N_j - BS)| \quad and \quad |D(N_i - N_{j)}| \leq r_i \quad \forall_j \quad where \ \ j = 1,2,\dots,n$$

This type of selection criteria is used in [147].

- In the case where nodes are deployed in deterministic and gradient fashion i.e. lower ID nodes are in higher proximity to the BS than the higher ID nodes. CH selection is based on the node ID. The node N_i having lowest ID among its neighboring nodes $|D(N_i - N_{j)}| \leq r_i$ is supposed to be selected as cluster head in this scenario.

$$\mathrm{ID}_{N_i} < \mathrm{ID}_{N_j} \ \text{ and } \ |D(N_i - N_{j)}| \leq r_i \quad \forall_j \quad where \ \ j = 1,2,\dots,n$$

This type of selection criteria is used in [148].

- Nodes are randomly selected as CHs, based on some probability calculation and its comparison with some randomly generated number between [0, 1]. Such style of CH selection is used in [127].
- Sometimes, topology information [146], [148] or the previous activity of the sensor node as cluster head is also considered for the selection of cluster head.

- Some special calculations either comprising of a combination of above-mentioned parameters or different parameters like pheromone concentration in Ant Colony (AC) inspired algorithms, energy welfare function, etc. are used for the selection of CH. Such style of CH selection is used in [137] [17].

All the above-mentioned selection criteria have their advantages and disadvantages depending upon the deployment scenario, network type, and application as well. Once a node is designated on the CH status, all its responsibilities raise it to come into action to satisfy them.

3.2.2 Cluster Head Rotation

During the tenure of working as CH, time comes when the performance optimality of cluster head turns to non-optimality. The CH is no more an optimal choice to stay as the head of the cluster since its priority over other member nodes become devalued due to its decrease in characteristic's value especially the energy. So, its designation must be rotated to transfer this role of being heading the cluster to some other suitable node. This process is called as cluster head rotation or reselection. The way, this designation is rotated and to whom it is assigned matters much especially with respect to energy consumption. Inter node communication for information collection, CH selection process and disseminating the decision are the main factors in it.

In our proposed solution with the name TLPER [17], we take nodal density and geographical location of nodes to decide centrally at the BS about the cluster heads and distributed selection of cluster members. Their proposed design has involvement of assistant cluster heads with LBT (Load Balancing Threshold) and RTT (Role Transfer Threshold) techniques. On approaching LBT, a node having highest energy level in the cluster called assistant CH is selected to share the load of CH. CH uses this ACH as its forwarding node rather than directly send the data to CH of next cluster. ACH either sends this received data directly to BS or to the next ACH of adjacent cluster. Using the dynamic power adjustment technique, energy utilization in data transmission is saved since ACH is far nearer to CH compared to CH of next cluster.

Another idea of introducing the assistant clusters is introduced by Dajin Wang [149] for power mitigation. He names these assistant clusters as partaker nodes. These special nodes assist the CH in the routine job of data collection. Instead of having CH to collect data solely from all sensors in the cluster, a certain number of partaker nodes participate in data collection. They help to collect the raw data, and perform initial data aggregation and processing before transferring data to the CH. With partakers, a portion of power that would have been consumed by CHs is transferred to partakers.

The literature is very rich in routing algorithms with various techniques of cluster head rotation. They are either ramification of one another with turning of calculation parameters [150] by varying their weight, or merger of different techniques [98]. In the subsequent part of this continuing section, an abstract view of CH rotation techniques based on basic evaluation parameter is presented.

At this stage of network when there is need of cluster head rotation for the reason of healing the disconnected regions and to distribute the energy consumption among all the nodes in both homogenous or heterogeneous networks, the energy delta (ΔE) between the network nodes and even between the cluster nodes becomes big. So, the following selection criteria can be a good option for choosing the CH.

- The energy of a node N_{E_i} is higher than the average energy of all nodes $\frac{1}{N}\sum_{j=1}^{n} N_{E_j}$, that are the members of cluster C_i and the difference in distance from N_i to N_j i.e. $D(N_i - N_{j)}$ need not to be satisfied.

  $$N_{E_i} > \frac{1}{n}\sum_{j=1}^{n} N_{E_j} \ and\ j \in C_i$$

  $$\left|D(N_i - N_{j)}\right| \leq r_i \text{ or } \left|D(N_i - N_{j)}\right| \geq r_i \quad \forall_j \quad Where \quad j = 1,2,\dots,n$$

Similar style of selection criteria is used in [142].

- The node having lowest energy consumption ratio R_{EC_i}among the individual energy consumption ratio of all the nodes R_{EC_j} of same cluster, say C_i.

  $$R_{EC_i} > R_{EC_j} \quad \forall_j \quad Where \quad j = 1,2,\dots,n$$

  and

  $$R_{EC_i} = \frac{(E_0 - E_1)}{E_c}$$

  Where E_0 is initial energy, E_1 residual energy and E_c is current energy.

  Similar style of selection criteria is used in [138].

Apart from the above mentioned CH rotation criteria, the selection criteria for the same that are mentioned under the heading of the initial round is also considered for the rotation of CH [151].

In most of the cases, cluster designing process is re-initiated once rotational criterion is met that is usually the energy level of a node [152] rather than letting the clusters unchanged and just the designation of CH is transferred to some suitable predecessor [153]. Although, the choice of rotational criteria varies from scenario to scenario and application to application yet the energy consumption factors at network layer during the routing process must be considered. The most pinching factor among those is extensive message exchange with larger packet size.

The process of CH election and rotation is controlled in different ways.

a. From Base Station [86]
b. Randomly selected [97]
c. Manually programmed as CH
d. Probabilistic selection of CH [154]

3.2.3 Cluster Member Selection

Once cluster head CH is selected, it broadcasts the membership or join request message ($join\_req\_msg$) to the nodes N_j in its foot print (communication range) r_i. Message recipient nodes reply with $join\_acpt\_msg$ message to give their consent of being part of the cluster as its members. If a node k receives $join\_req\_msg$ from more than one cluster heads then normally the decision of joining is based on the following criteria.

- If the received signal strength of $join\_req\_msg$ by cluster head i at node k i.e $RSS_k(CH_i)$ is greater than that of individual received signal strength all other cluster heads $RSS_k(CH_j)$ then node k sends $join\_acpt\_msg$ to CH_i.

$RSS_k(CH_i) \geq RSS_k(CH_j) \quad \forall_j \quad where\ j = 1,2,3, \dots n \quad and \quad |D(CH_i - k)| \leq r_i$

This cluster member selection technique is used in [137].

- Node k sends the $join\_acpt\_msg$ message to CH_i in response of its $join\_rqst\_msg$ if energy of inviter CH_i (E_{CH_i}) is more in comparison to the individual energy of competitor inviter CH(s) E_{CH_j}.

  $E_{CH_i} \geq E_{CH_j} \quad \forall_j \quad where\ j = 1,2,3, \dots n \quad and \quad |D(CH_i - k)| \leq r_i$

- Node k sends the $join\_acpt\_msg$ message to CH_i to accept its join invitation if communication cost of inviter CH_i CC_{CH_i} is more in comparison to the individual communication cost of competitor inviter CH(s) i.e. CC_{CH_j}.

  $CC_{CH_i} \geq CC_{CH_j} \quad \forall_j \quad where\ j = 1,2,3, \dots n \quad and \quad |D(CH_i - k)| \leq r_i$

That communication cost may be the combination of different parameters like distance between node and the candidate cluster head and distance between candidate cluster head and the base station [142].

- Node k sends the $join\_acpt\_msg$ message to CH_i to become its member if degree of inviter CH_i i.e. D_{CH_i} is less in comparison to the individual degree of competitor inviter CH(s) i.e. D_{CH_j}.

  $D_{CH_i} \leq D_{CH_j} \quad \forall_j \quad where\ j = 1,2,3, \dots n \quad and \quad |D(CH_i - k)| \leq r_i$

This cluster member selection technique is used in [79].

- In the case of a tie in first affiliation criterion such as signal strength, another criterion for affiliation of node to CH is selected such as energy of the candidate node [17].
- Composite key for the affiliation to CH comprising of above mentioned selection criteria is also an approach in practice [155]. Apart from it the affiliation criteria for the same mentioned under the heading of initial round is also considered such as distance [110].

3.2.4 Summary

Above discussed cluster head selection, cluster head rotation and cluster member selection techniques and criteria and their ramification are common in the literature on clustered network and routing there on. All have their advantages at their usage in the appropriate time, space and scenario. Demerit only lies when there is time, space and scenario inappropriateness in their usage. More-over, there also lies the sense of precedence in choice among them. Our proposed algorithms for CH selection, CH rotation, and CM selection are also the ramifications of existing solutions. The suggested improvements come up with the ideas that awesomely ameliorate the network performance which is noticeably over performing the competing solutions.

Considering the similar scenario among the competing ideas is the prime step for fair competition. Our proposed solution for CH selection takes the scenario of random deployment of homogenous nodes. The ideas for such scenarios that take energy as the CH selection criteria such as [97], and [156] may suffer from network cluster with a big difference of their sizes. It may also result in either very small cluster size or very large cluster size. If the former case happens frequently then, the number of clusters is of big count. If the other case occurs then clusters become overburdened, that may result in early drainage of CHs' energy. These issues can be observed in the designed clustered networks of [97], [138], [139], and [156]. Similar hazards may also exist in the idea where nodes are randomly selected as CHs such as by LEACH [91] and some of its ramifications like [86], and [131].

In the initial round, network nodes' energy is almost same. So, node degree seems to be a suitable parameter for selection of CH. This choice has the solutions for aforementioned issues that are raised due to choosing energy as the CH selection parameter. Our proposed solutions; MCDA and EMCDA that are discussed in section 4.4 and section 4.6 respectively follow the same strategy. Composite parameters such as node energy and node degree as is in [110], node energy and distance to BS as is in [137] can also be used but these are suitable in CH rotation. Most of the algorithms in the literature follow the idea to iterate the same process for CH rotation as is for the CH selection in 1st round. This style is adopted in [110], [97], [137], [139], and [156]. This iteration is scheduled on completing every round. Such as in LEACH. Here one round means aggregation of data from CMs at CH and communication of that aggregated data ultimately to sink. This style takes a big share of node's total energy especially in re-clustering process. A better idea is to set a threshold to trigger the CH rotation process as is in [157] where CH rotation process is only initiated on decrease in node density. We believe that this method is much more energy aware compared to the previous one where there is complete re-clustering on every round. This energy aware method is adopted in [17] and [157], etc.

The critical point in this approach lies in selecting the threshold value of the selection parameter and the way, how the next optimal candidate is to find for replacing the existing

CH. Choosing the threshold value of node's degree to be selection parameter for CH rotation makes the management tougher compared to choose the node's energy for the same purpose. In the first case, triggering of re-clustering process is totally dependent on changing the CH's degree that only occurs if there is death of CM. This may mean that along with the death of one node, energy of other CMs is also decreased to the lowest if not totally drained out since they are also participating in the sensing and communication activities of cluster. Another dark aspect of not considering the CH's energy itself is that CH goes to dead before having any change in its degree (no. of CHs neighbors i.e. CM). More-over, prioritizing the first case may also result in very early initiating the re-clustering process due to node's malfunctioning or node's death.

In order to achieve the distinguished energy awareness in cluster head rotation, our proposed technique; ECHeaRT exploits threshold levels for CH's energy in two steps; LBT and RTT. Empirical results in comparison to state-of-the-art techniques reflect positive improvements in network performance due to this introduced CH rotation technique. This also offers effective solution for the aforementioned issues that are faced in algorithms like [157] due to selecting node degree as the parameter for initiating CH rotation process. This proposed work is explicitly discussed in section 5.2.2 that is the extension of our published work [17]. Another attractive point is that CH selection and CM selection are already the part of our proposed cluster designing process; Multilayer Cluster Designing Algorithm. So, no process is initiated dedicatedly for it.

3.3 Routing In Clustered Network

In this subsection, various state-of-the-art strategies covering aspects from network design to network routing in cluster based network environment are presented.

Yu *et al.* [157] have proposed two algorithms for large-scale homogeneous wireless sensor network. First is energy efficient and dynamic clustering technique that is a dynamic distributed cluster designing algorithm. Second is energy efficient and power-aware technique that is a multihop routing algorithm based on the clustered architecture. By monitoring the received signal power from its neighboring nodes, each node estimates the number of active nodes in real time. Then it computes its optimal probability of becoming a cluster head, so that the amount of energy that is spent in both intra-cluster and inter-cluster communications can be minimized. Hence, the node with highest node degree is selected as cluster head. B_{min} is the minimum battery power required for a node to be considered as active. The designed clusters are of unequal size since the CMs are affiliated to the CH based on their closeness to it. Their closeness is calculated by RSSI. The authors claim that they follow the process of cluster formation to that of LEACH by using advertisement and join-request messages. Decrease in the node degree initiates the re-clustering process where the clusters are merged to maintain the cluster normal size.

A route request packet is flooded in the network to the BS. Each path node embeds its transmitting power and path cost to the packet and forwards it to its next hop. BS receives multiple copies of the sent route request packet and sends the route reply message over multiple selected candidate routes. Reply message comprises of total path cost and a reference value $B_{ref}(t)$ to evaluate the path nodes. If the path node does not satisfy the required battery power level then the candidacy of its route is cancelled. Upon receiving the multiple copies of reply message from BS, the most optimal route with respect to both energy efficiency and power awareness is selected to send data to the BS.

Dali Wei *et al.* [151] have proposed a distributed clustering algorithm, Energy Efficient Clustering with direct hop intra-cluster routing and multi-hop source to sink routing in homogenous wireless sensor network. They assumed to divide the network into rectangular regions. In proposed solution, cluster designing algorithms encompasses the selection of Candidate CH, election of CH among candidate CHs, joining of nodes to the CH based on RSSI value. If there are still undecided nodes after completion of formal cluster formation process then they dynamically adjust their power level to make them associated with nearest CH. Each node calculates the P(*J*) value i.e. ratio of initial energy level of the node to the average initial energy of the network and generates a random value between 0 and 1. If the generated random value is less then calculated P(*J*) value then, it is included in the CH candidate set. From this set, the node with the highest energy level is elected after making decision by exchanging their energy levels among each other. Elected CHs transmit "*CH announcement*" message for the invitation to remaining undecided network nodes to affiliate with it. Nodes associate to CHs sends “*CH confirmation*” message. At the end of the cluster formation phase, there may still be a few sensors that may not have received any announcement packets and remain undecided nodes. A remedy for such case is given by the authors in the form of dynamic power adjustment by increasing their transmission range and seeking the closest CH to associate with.

Authors have proposed distributed intra-cluster routing based on two ideas, i) reduction in overhead in route discovery, and ii) balancing the energy consumption among CHs. CH dynamically adjusts its transmission power and sends a route request packet in its neighborhood. Each recipient node calculates a route reply timer whose value is inversely proportional to its residual energy level. The node with the earliest expired timer sends back a route reply packet to the requester CH. All other listeners of this message then cancel out their timer and so the transmission. In this way, all CHs make their way towards BS for communication of data.

S. D. Muruganathan *et al.* [86] have proposed a centrally designed and evenly distributed clustering algorithm with the name BCDCP (Base-Station Controlled Dynamic Clustering Protocol). BS performs iterative clustering algorithm to form the desired number of clusters. All the network nodes communicate their energy level to BS. It selects those nodes to be candidate CHs that have their energy level higher than the average energy of all the nodes. In BCDCP, nodes use dynamic power adjustment to communicate with the far distant placed BS. Among those two far distantly placed nodes are identified for partitioning the network into two big clusters. All the other nodes are evenly affiliated to these two elected CH based on closeness to it. Two high energy nodes among the candidate CH nodes from each of the designed clusters are selected. These selected nodes are at far distant from the existing CHs. Then these are again partitioned into sub clusters. This process is iterated until the required number of clusters is designed.

Once the clusters and the CH nodes have been identified, the BS chooses the lowest-energy routing path by connecting the CH nodes using the minimum spanning tree and forwards this info to the sensor nodes along with the details on cluster groupings and selected cluster heads. One node from this CHs chain is randomly selected to communicate the received data from other cluster heads to the BS. Assigning the time slots to the CM nodes to communicate with the CH and to the CH nodes to communicate with the next hop CH node until BS is assigned by the BS using TDMA schedule. BCDCP uses CDMA technique to counteract the problem of radio interference caused by the neighboring clusters. Sensed data by the sensor nodes is sent to the CH where it is fused and transmitted to the BS via CH-to-CH hoping. Same process of cluster head selection, cluster designing, and the BS performs route establishment on each round.

Proposed Mechanism; EADUC (Energy Aware Distributed Unequal Clustering) by Yu *et al.* [138] is an energy aware routing algorithm for cluster based wireless sensor networks. They introduced unequal sized clusters for the remedy of hot spot issue that results in better network life time. Designing of clustering topology comprises of neighbor node information collection phase, cluster head competition phase and cluster formation phase. These constituents make up setup phase. Each one is given a specific duration i.e. T_1, T_2 and T_3. Next to it is the data transmission phase. To start the cluster formation process, BS broadcasts a signal at a certain power level. Each node can compute its approximate distance to the BS based on the RSSI. In first phase, each node broadcasts a *Node_Msg* message within its radio range $'r'$ having node id and its residual energy E_r. Based on collected information, each node calculates average residual energy of its neighbor nodes. Next calculation is of waiting time *t* using following formula given in Equation 5.

$$t = \begin{cases} \frac{E_a}{E_r} T_2 V_r, & E_r \geq E_a \\ T_2 V_r, & E_r < E_a \end{cases} \quad (5)$$

Where V_r is a real value randomly distributed in [0.9, 1] which is introduced to reduce the probability that two nodes send *Head_Msg*s at the same time. Each node waits until this calculated time prior to broadcast *Head_Msg* message.

To start cluster head selection competition phase, each node compares its average residual energy to its neighbor's calculated average residual energy and decide to be a cluster head or not. After waiting for calculated *t* time, decision for the nodes to be a cluster head is broadcasted within their calculated radio range. If a node does not receive any *Head_Msg* message until the expiry of its time *t* then it broadcasts the *Head Msg* within radio range R_{C_i} to advertise that it will be a cluster head. Since the competition radius R_C determines the size of cluster that is based on the proximity to the BS. Each node calculates its own value for R_C using the formula as given in Equation 6.

$$R_C = \left[1 - \alpha \frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}} - \beta \left(1 - \frac{E_r}{E_{max}}\right)\right] R_{max}, \qquad (6)$$

where d_{max} and d_{min} are the maximum and minimum distance from the nodes in the network to the BS, $d(s_i, BS)$ is the distance from node s_i to the BS, α and β are weighted factors having values in $[0,1]$, and R_C^0 is the maximum value of competition radius. This makes the cluster size bigger for farther elected cluster head and smaller for nearer elected cluster head. Each non-cluster-head node chooses the nearest cluster head and sends the *Join_Msg* which contains the, *id* and residual energy of this node. Authors also modify this technique for heterogeneous networks by introducing energy factor in radio range competition radius in order to maximally exploit the higher energy nodes. Cluster member node senses the environmental physical quantity,, communicates it to its CH. CH collects the data, aggregates it and transmits it to that node in its communication range which is closest to the BS in case distance of CH from the BS is less than the defined threshold distance. Inverse case results in direct communication of data If more than one nodes with same 'distance to BS' exist then higher precedence is given to highest energy carrying node.

3.3.1 Summary

Algorithms that are explained in section 3.3 discuss the network design to network routing in cluster based WSN environment. Table 3.2 gives an abstract view of comparative analysis of clustering algorithms on various network design and operational parameters.

Table 3.2: Comparative Analysis of Clustering Algorithms on Various Network Design and Operational Parameters

	[137]	[139]	[138]	[110]	[97]	[157]	[147]	[142]	[156]
Node Type	Both	Homogenous	Both	Homogenous	Homogenous	Homogeneous	Homogenous	Homogenous	Homogenous
Comm. to Sink	Multi-Hop	Multi-hop	Multi-hop	Multi-Hop	Direct Hop	Multi-Hop	Multi-Hop	Multi-Hop	Multi-Hop
Cluster Size	Unequal	Unequal	Unequal	Unequal	Unequal	Unequal	Unequal	Unequal	Unequal
Cluster Designing	Distributed	Distributed	Distributed	Distributed	Centralized	Distributed	Centralized	Distributed	Centralized
CH Election Criteria	Residual Energy (RE) and Distance	Residual Energy	Ratio of Avg. RE of neighbor nodes and RE of Node itself	Node degree and Node energy	Energy	Node Degree	Distance to BS (1^{st} round) Distance to BS and RE (Later rounds)	Highest RE among neighbor's Nodes	Node Energy
Inter-Cluster Comm. Style	CH to CH	CH to CH	CH to Max Energy CH	CH to CH	-	CH to CH	CH to CH	CH to CH	-
Intra-Cluster Comm. Style	-	Direct	Direct	Direct	Direct	Direct	Multi-Hop (Chain of CM Nodes)	Direct Hop	Direct Hop
CH Rotation	On each round	On each round	-	On each round	On each round	On the decrease in Node density	On each round	On each round	On each round

A brief description of parameters used in Table 3.2 is given below.

- **Node Type**

  Category of nodes according to their configuration

  - *Homogeneous:* All the network nodes are of the same configuration (energy, memory, processing power, etc.)
  - *Heterogeneous:* Nodes in the network are of different configuration (energy, transmission range, antenna gain, processing power, etc.)

- **Communication to Sink**

  On data collection at CH, communication style is chosen to get it reach BS either through direct communication or multi hop communication.

  - *Multi hop:* CH communicates the data to BS through some transient node (CH or gateway node).
  - *Direct Hop*: CH communicates the data to BS without using any transient node.

- **Inter-Cluster Communication Style**

  Communication of data from one clusters to another adjacent cluster.

  - *CH – CH*: CH communicates the data to its next CH.
  - *'-'*: CH either transmits the data directly to BS or the authors does not mention this routing aspect in their paper at all. Another possibility exists i.e. CH does not communicate the data to next CH rather it is a gateway node that is selected to transmit the data directly to BS.

- **Intra-Cluster Communication Style**

  Cluster member node communicates the data to CH either directly or indirectly.

- *Direct*: CM node communicates sensed or collected data to CH without using any transient node.
- Multi Hop: CM node communicates sensed or collected data to CH thorough some transient node.
- '-': Authors do not discuss intra-cluster communication style in their paper.

- **Cluster Size**

  Size of the cluster in the network with respect to the number of CM nodes.

  - *Equal*: Number of CM nodes in network clusters are almost same.
  - *Unequal*: Number of CM nodes in network clusters are variable enough to make their size very different from each other.

- **Cluster Designing**

  The process of grouping network nodes in clusters based on some defined parameter.

  - *Centralized*: The process of cluster designing is controlled directly from BS.
  - *Distributed*: The process of cluster designing is distributed. Nodes communicate with each other to do this process.

- **CH Election Criteria**

  A node is elected to head the activities of the cluster that is called CH. This election is based on some election parameter.

  - CH is elected based on residual energy of node, position of the node, or based on some calculation like ratio of average residual energy of neighbor nodes and residual energy of the node itself.

- **Power Adjustment**

  The node adjusts its transmission power for communicating its data to the destination node.

  - *Static*: Node's transmission power remains same i.e. neither it is increased nor decreased.
  - *Dynamic*: Node either increases or decreases its transmission power according to interacting situation.

- **CH Rotation**

  Role of CH is transferred to a suitable node based on some selection parameter

  - CH rotation is performed either on each round or on the decrease of some node's characteristic.
  - '-': Authors do not discuss this aspect in their paper at all.

In view of the long related literature on energy aware aspect of routing from the start of WSN technology until 2014, it is not an exaggeration to narrate that this topic is one of the hottest topics of research in research community that is working on WSN domain. This target is tried to achieve by improving various factors (as discussed in section 2.1) at number of functional aspects such as communication to sink, cluster designing, CH election, inter-cluster and intra-cluster communication style, and CH rotation. Direct hop communication from the source node to sink node as is adopted in [91], and [97] is energy aware solution for small networks. This limitation is removed by multi-hop communication style which also has its number of variants. Some algorithms are just two level multi-hop from source to sink as in [96] and some are pure multi-hop without any limit of hop count from the source to sink as in [86]. This last fashion of communication is This preferable choice among other two options i.e. direct hop and two level multi-hop. In our paper [98], we have given a hybrid solution to improve the network efficiency further with respect to energy consumption in the routing process. The same hybrid technique is analyzed for its dependability and reliability in intra-cluster routing technique in temperature sending and battlefield applications in [158]. In our proposed solution for energy aware routing that is discussed in section 5.3, the same hybrid technique puts its contribution for achieving its target. This solution can also be a remedy for hot spot issue. Another important functional aspect is of the cluster designing over which we have already given a critical review on existing related literature in section 3.1.1. Section 3.2.4 also presents a concise critical review based on energy efficiency of constituents of the routing process i.e. cluster head selection and cluster head rotation.

Apart from these, the inseparable elements of routing are inter-cluster and intra-cluster communication style. Most of the proposed ideas in the relevant literature follows the direct hop intra-cluster communication style i.e. from CMs direct to the CH. The algorithms in [110], [97], [138], [139], [142], and [156] show the same style of intra-cluster communication. This method is not suitable for large size clusters. Also, the total load of data collection from its CMs and neighboring CHs and the load of forwarding the collected data to next CH or direct to BS is on the CH. Another style is of multi-hop that is used in [158], and [147] is more suitable for large size clusters. Our proposed work on this issue i.e. explained in section 5.3 has the idea of direct intra-cluster communication due to average size of cluster.

Very small size clusters and very large size clusters have their own disadvantages that affects especially on energy consumption adversely. CH to CH inter cluster communication style as in [110], [137], [147], and [142] usually require smaller size of clusters as CHs are in normal communication range of each other. For average and very large cluster size and even in some cases of smaller clusters size when CHs are on opposite ends of clusters, the direct CH to CH communication is not possible in cost effective way. This situation of accessing the next forwarding node (CH) becomes more worsen when current CH is to access the next more energy carrying CH in the network as in [138]. As a remedy of this issue, some forwarding node is chosen between the two neighboring CHs. This strategy makes the CH to CH communication possible even in case of large size clusters, yet this opens the new challenges of finding the optimal bridge node. This become also an overhead if a separate message exchange process is started to collect the value of selection parameter. In our previous work [17], we adopted the same strategy. Our current solution on this underlying discussed issue is the constructive ramification of this idea but the initializing of a separate message exchange process for finding the optimal bridge node is strictly avoided. This is achieved by listing down the most suitable forwarding node at each node is the part of cluster designing process. Section 5.3 gives a detailed discussion on it. Also Figure 5.3 depicts different roles of network nodes in rotation of forwarding node.

Chapter 4

4 Energy Efficient Cluster Designing

4.1 Introduction

Although cluster based network is a proven architecture for energy aware routing since the architectural setup of clustered network has self-support in the conservation of energy, yet more attention is required to ameliorate the energy consumption aspect of its cluster designing process. Literature is rich in cluster based routing protocols that mostly encompasses cluster designing, route establishment and cluster head rotation processes. Cluster designing; the core theme of this chapter, consists of cluster head selection, cluster member affiliation to CH and time slot assignment for communicating the sensed data to CH. All the proposed algorithms for the same either accomplish these processes with central control of BS [86] or locally controlled distributed style [137]. Both the techniques have their pros and cons.

In Centralized Cluster Designing (CCD), the deployed nodes communicate the required decision parameter values (energy level, node degree, geographical location, and output of some decision metrics' calculation depending upon the underlying CCD algorithm) to the BS. This communication is either through direct hop [91] or multi-hop using transient nodes [86] depending upon the network scale. Base station applies some clustering algorithm: K-Nearest Neighbor [87], K-Means [88], Centroid [89], or Affinity Propagation [90] etc., for the selection of cluster head and communicates the decision with the deployed network nodes. Figure 4.1 depicts the centralized cluster designing approach where all the network nodes are communicating their information to the BS. BS elects the most suitable CH out of the received information, and the decision is communicated to the elected CHs. CH then broadcasts its status. Listener nodes affiliate themselves to the most suitable CH. Proximity to CH, distance of CH to BS, energy, load or the combination of any of these can be the affiliation decision parameters.

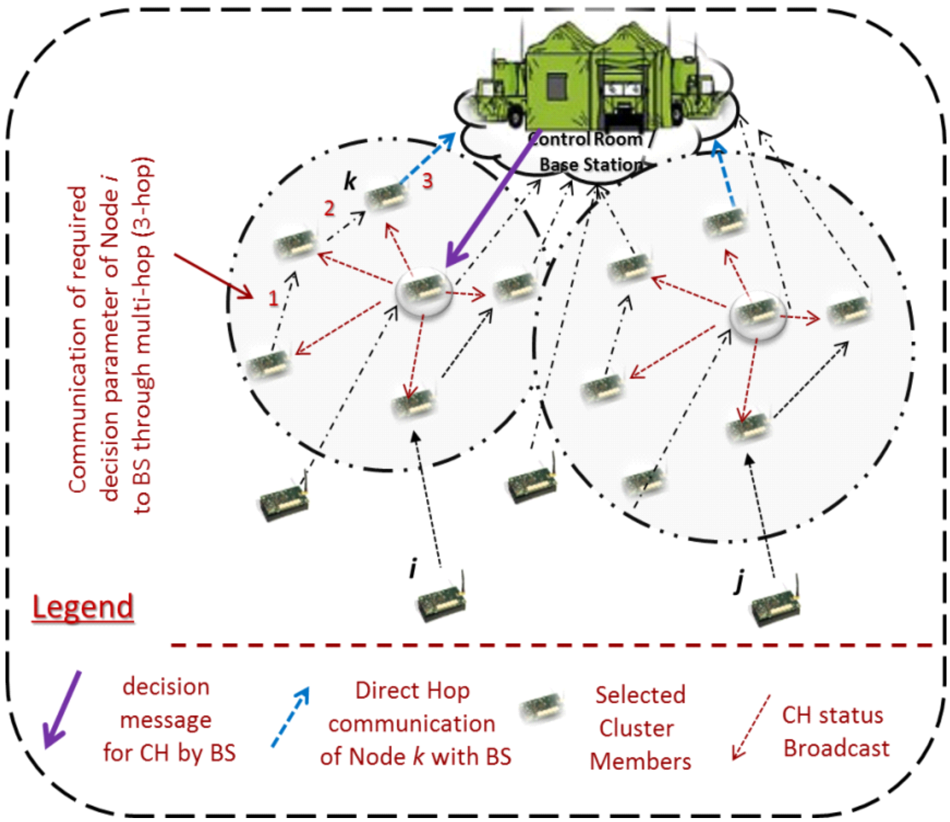


Figure 4.1: A Typical Centralized Cluster Designing (CCD) Approach

In local or Distributed Cluster Designing (DCD) approach decision of CHs are made locally through various fashions as available in the literature. The most prevailing style is exchanging the value of decision metric (energy level node degree, geographical location, and output of some decision metrics' calculation depending upon the underlying DCD algorithm) among neighboring nodes. The node that has the most optimal value among its neighbors is elected as CH. Another style is a random selection based on logical comparison of generated random value between [0, 1] with some calculated probability [93] [96] [97]**.** Elected CH advertises *Join_Request* packet. Recipient nodes make the joining decision depending upon proximity to CH, distance of CH to BS, energy of CH, load on CH or the combination of any of these.

Route establishment process may start either during this cluster designing process or after it. The protocols that follow the former case are categorized under on-demand cluster-based algorithms where the existing traffic is exploited to piggyback cluster-related information to establish paths [159]. Some of the on-demand cluster-based algorithms in the literature are by Forster *et al.* [160] and Zeghilet *et al.* [161]. The protocols categorized under the latter case are qualified as pre-established cluster-based algorithms [159]. In these types of protocols, after the cluster designing the inter-cluster communication is ensured using traditional flooding among cluster heads. This can also be done by recursively executing the clustering algorithm to obtain a hierarchy of cluster heads rooted at the sink. [145] is a typical example of the pre-established cluster-based algorithm. In spite of various advantages of each of the techniques, one drastic energy squeezing common disadvantage of the two is too much broadcasting especially in large networks as well as message exchange until some final decision is made. So, a hybrid solution exploiting the pros of distributed and centralized cluster designing approaches and escaping the cons of these both techniques is highly appreciable. To the best of our knowledge, this is first of its research work ever discussed in detail.

4.2 Assumptions and Definitions

In this Section, the assumptions that are made during the design of network and simulation model are presented. Some of the scenario-related definitions are also given. Guidelines for few of our assumptions are taken from [86].

Assumption 1 (Homogenous Nodes): All the sensor nodes have the same configuration; sensing and communication range, i.e. 100m and have the same energy level, i.e. 15J.

Assumption 2 (Communication Radius Model): The communication range of a sensor node $'A'$ has the radius ‘R’ that is centered at ‘c’. It can be defined as $CR(c, R) = \{A, q \in S: |D(A - q) \leq R_A\}$. CR represents communication radius, S represents the set of deployed nodes and $D(A - q)$ is the distance between nodes A and q in the deployment area. R_A is radius of sensor node $'A'$.

Assumption 3 (Reliable Communication Link): We have assumed AWGN channel and have adjusted Signal to Noise Ratio (SNR) in such a way that signal reaches the destination node with an energy that the overall detection probability is more than 0.5. In our case, the threshold value of detection probability is 0.4 for a readable received signal.

Since wireless sensor network is of constraint environment especially from the perspective of node energy, so we avoided acknowledgement. In case of introduction of link error, the probability of better working of proposed scheme will be affected. Such as increase in possibility of selection of non-optimal decision maker and forwarding node, less suitable cluster head, and more unattached nodes during cluster formation etc. The more is the link error, more adverse is its effect on network performance.

Assumption 4 (Reliable Network Nodes): The deployed network nodes are reliable and secure and will not be malfunctioning or be hacked or die suddenly. The deployed nodes are considered dead when their energy approaches a defined threshold, say 0.5J in our case.

Definition 1 (Communicating Neighbor Set): All the nodes (q_i) which fulfill the following criteria are considered in the neighborhood of node p. $|D(p - q_i)| \leq R_p \quad \forall_i$ Where i = 1, 2, 3…n and R_p is the communication radius of node p.

Definition 2 (Medium Scale Network): If all the deployed nodes have direct communication access to the BS then the network is considered to be Medium Scale Network (MSN). In our simulation environment, the network comprising 100 nodes deployed in area of 100m x 100m is considered as MSN. This definition can be modeled as $\forall p \Lambda\, p \in S$, $|D(p - BS)| < R_p$ where p is a node among the set $'S'$ of deployed nodes and $D(p - BS)$ is the distance between any of the deployed network nodes say p and the BS. R_p is the communication radius of node p.

Definition 3 (Large Scale Network): If any of the deployed nodes doesn't have direct communication access to BS then the network is considered to be Large Scale Network (LSN). In our simulation environment, the network comprising 100 nodes deployed in area of 200m x 200m is considered to be LSN. This definition can be modeled as $\exists p\, \Lambda\, p \in S, |D(p - BS)| > R_p$ where p is a node among the set $'S'$ of deployed nodes and $D(p - BS)$ is the distance between any of the deployed network nodes say p and the BS. $\mathrm{R_p}$ is the communication radius of node p.

4.3 Energy Consumption Model

In our research work, we assume the following radio model. Almost similar model is used in [91]. Here, the radio dissipates $E_{elec} = 50\, nJ/bit$ to run the transmitter and receiver circuitry. For the transmitter amplifier, it dissipates $\varepsilon_{amp} = 100 \frac{pJ}{bit}/m^2$ in order to achieve an acceptable $\frac{E_b}{N_o}$. Hence, for the transmission of $k\ bit$ message at a distance d by using the aforementioned radio model, the radio expends:

$$E_{T_x}(k,d) = E_{T_{x-elec}}(k) + E_{T_{x-amp}}(k,d)$$

$$E_{T_x}(k,d) = E_{T_{elec}} * k + \varepsilon_{amp} * k * d^2$$

and for receiving this message, the radio expends:

$$E_{Rx}(k) = E_{Rx-elec}(k)$$

$$E_{Rx}(k) = E_{Rx-elec} * k$$

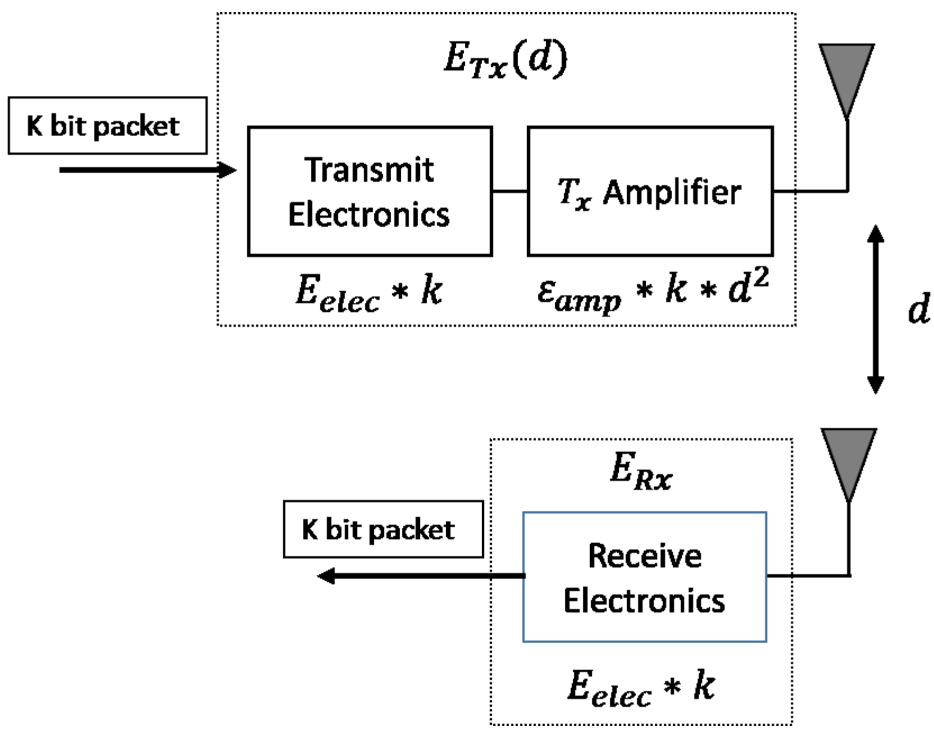


Figure 4.2: First Order Radio Model [91]

4.4 Proposed Solution

Any clustering algorithm normally comprises three phases, namely set-up phase, steady phase and routing phase. The first one is related to cluster designing where all communication process works for cluster designing. In the literature this phase comprises CH election/selection, CM selection, and route establishment. This phase is called off-line phase or passive phase since all messaging is of control packets, and no data are traversed in the network. The other phases come in operational or active phases, and data are in the network for aggregation and routing. Our proposed idea has distinction in its approach of making up multilayer design of wireless sensor network. To the best of our knowledge, no such analytical research with simulation-based comparison to CCD and DCD is seen in the literature. From the perspective of network topology, our proposed is best suited for static network. In case of mobility in nodes, it has adverse effect on any network designing and routing protocol and any network infrastructure as well. With mobility the routing paths in proactive routing protocol are changed and overall overhead is increased. In case of reactive protocol, the established paths are greatly affected by mobility and it needs to advertise many route request. In cluster based network, mobility causes frequent movement of cluster head and thus formation of new cluster is required. So, it has adverse impact on network performance. In our dissertation, we only considered the scenario of static network.

The proposed solution in the above context is explained in the subsequent paragraphs with comprehensive representation in the form of figures (Figure 4.3, Figure 4.4, Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8) and tables (Table 4.3 and Table 4.4). The phase of cluster designing comprises three steps: self-organization, flat layer design, and clustered layer design. Figure 4.4, Figure 4.6, and Figure 4.8 shows the pseudo code of each of these steps. Description of terminologies used in pseudo code is given in Table 4.2.

4.4.1 Self-Organization

When the nodes are deployed either uniformly or randomly, after switching on their active mode, they just give a blink and broadcast a beacon message to show their existence. The neighboring nodes receive their beacon messages, set up their neighbor table, calculate the link quality or do the necessary calculations for any future decision making depending on the underlying algorithm. The energy consumption during this self-organization process is usually almost the same for all the routing/working algorithms and is not considered in the calculation of total energy consumption. We also will not be considering this energy consumption for finalizing the calculations in our results producing stage. The capabilities of this self-organization are widely exploited by exchanging the node status (location, energy level in case of heterogeneous network).

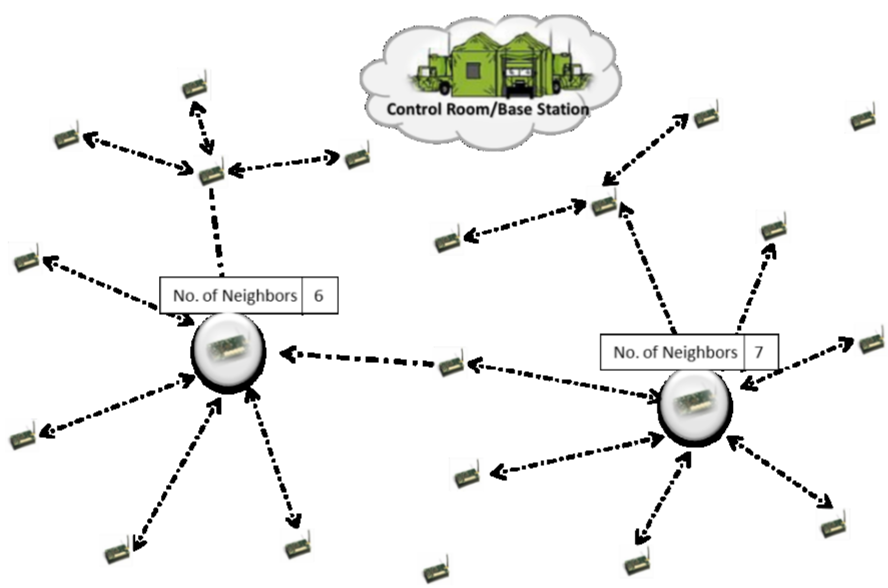


Figure 4.3: Self-Organizing step in MCDA and its exploitation for working of other steps in successful designing of energy aware wireless sensor network architecture

MCDA sets up neighbor table at each deployed node by just placing the neighbor count in it rather than all the info of neighbor nodes. This saves the resources. Figure 4.3 shows the typical functionalities of self-organizing along with example neighbor table in MCDA. The sample format of beacon packet that we are using in this mechanism is given in Table 4.1.

Table 4.1: Beacon Packet Format

8 bits	8 bits	8 bits	3 bits
Source Address	Destination Address	Packet Sequence no.	Packet Type

Since, the beacon packet are of limited types, so we just keep the size of his field small. Also the number of bits for source address and destination address varies with number of deployed nodes.

4.4.2 Flat Layer Design

One of the main issues that is usually mentioned in the context of multi-hop routing process is frequent depletion of energy of nodes deployed in the neighbor of BS. In the clustered network, the neighbor clusters of BS are overloaded due to being intermediate points of all paths approaching from different sources to BS. Moreover, energy is consumed during the cluster designing process. If the cluster is designing fashion of LEACH and its successors, i.e., V-LEACH, TL-LEACH, C-LEACH, etc. are followed, then the energy consumption would be drastically high. Also, the frequent rotation of cluster heads would be another additive danger to network life time [140]. To cope with all these dangers especially to clustered networks, our introduced strategy in MCDA gives a suitable solution to these issues.

BS broadcasts setup initialization message within range of 100m. The recipient nodes are within one hope to and from BS and termed as Layer 1 nodes $\left(Node_{L_1}\right)$ and this level of nodes is names as flat a layer (Line 1 to Line 4 of Algorithms 1).

ALGORITHM 1. MCDA functions for Flat Layer

Start

1. *Base Station Broadcasts* $\text{Msg}_{(setup_{init})}$
2. $R_{(B_{T_x})}$ = *100m*
3. *Set* $Node_{(R_x)} = Node_{L_1}$
4. $Node_{L_1}$ *Broadcast* $Cntr_{n_i}$
5. *Set Transceiver of* $Node_{L_1}$ *= Sleep mode for specific time interval*
6. **If** $Node_{(R_x)} \notin Node_{L_1}$ **Then**
7.   *Receive the packet*
8.   *Set* $Node_{(R_x)} = Node_{L_2}$
9. **End if**

End

Figure 4.4: Pseudo code—MCDA function for flat layer

The subsequent layers are defined on the basis of transmission range of previous layer nodes (first layer nodes in this case till now). These first layers nodes broadcast their neighbor count ($Cntr_{n_i}$) with in one hop range (Line 4 of Algorithm 1). The recipient nodes that are not from first layer set their level as second layer nodes (Line 6 to Line 8 of Algorithms 1). Figure 4.4 shows the pseudo code of MCDA function for flat layer and Figure 4.5 depicts this layered representation of the deployed network. The transmission range in outdoor environment in case of MICAz node is 75m–100m as mentioned in MICAz datasheet and in indoor environment 20m – 30m [2].

We started the network clustering from the outer boundary of the first layer (second layer) up to the network boundary. The cluster heads in the second layer are selected by the elected decision-maker nodes of the first layer as discussed in Section 4.4.3. This will save the energy that other cluster-based routing algorithms consume for frequent cluster designing in the neighborhood of the base station (as in DSS algorithms [93]) or re-clustering of whole network (as in centralized cluster-based networks). This also decreases the load on the neighbor nodes that ultimately does the load balancing and hence increases the life time of the network. In the next part of this Section, we will discuss the design of clustering layers.

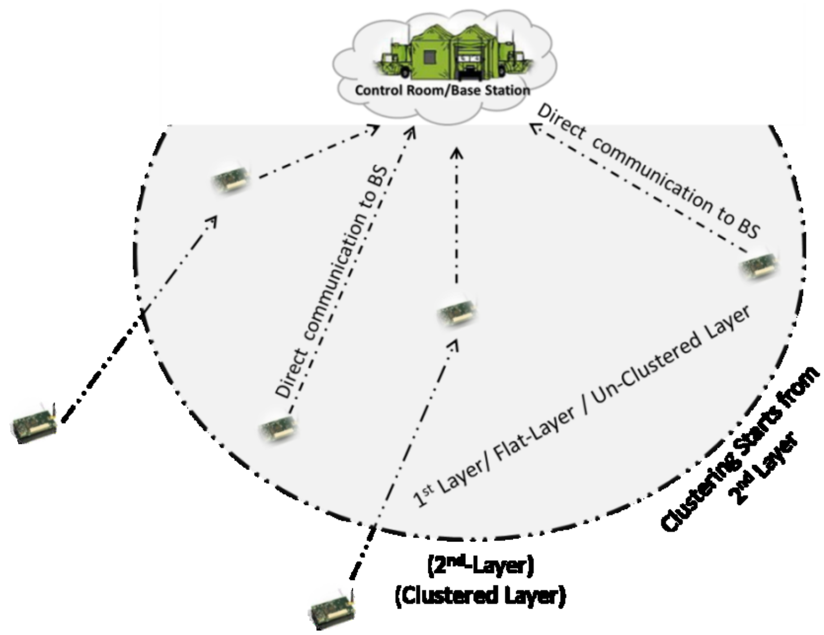


Figure 4.5: First Layer Designing in MCDA

4.4.3 Clustering layers Design

Centralized cluster designing requires all the network nodes to communicate their status info, especially the info of decision metric to the base stations, which consumes much of the nodes' energy. This becomes a much more energy-squeezing process in a large-scale network where direct hop does not work well due to a greater distance between source and destination than the nodes' normal footprint. Then multi-hop is the only solution for communicating the information of network nodes' decision metric to the BS. The overall energy consumption in such fashion of information collection is directly proportional to the network size. On the other hand, distributed cluster designing requires much of the inter-node communication to elect the cluster head first and then the cluster members.

Table 4.2: Description of Terminologies

Terminology	Description
$\mathrm{Msg}_{(setup_{init})}$	Set_up initialization message
$R_{(B_{T_x})}$	Broadcast transmission range
$Node_{(R_x)}$	Broadcast recipient node
$Node_{(dm)}$	Decision maker node
$Node_{(dm_{id})}$	Decision maker node Id
$Msg_{(r)}$	Reply message
$Node_{L_1}$	Layer 1 nodes
$Node_{L_2}$	Layer 2 nodes
Cnt_{n_i}	Neighbor count of node *i*
$Pkt_{(Seq\_no)}$	Packet sequence number
$Node_{(s_{id})}$	Sender node's Id
$Msg_{(reply_{n_i})}$	Reply message by node *i*
$Cnt_{(Postfix)}$	Postfix counter of packet sequence number
$Pkt_{(join_{rqst})}$	Join request packet
$Pkt_{(join_{acpt})}$	Join accept Packet
CH_i	i^{th} cluster head
$Pkt_{(CM_{cnt_{rqst}})}$	Request packet for the number of current cluster member nodes
$Pkt_{(CM_{cnt_{rply}})}$	Reply packet for the number of current cluster member nodes
$CM_{(\min\_cnt)}$	Cluster head having minimum number of cluster members

In this cluster designing method, the inter-node message exchange is in multiples of *n,* i.e., number of nodes. In this technique, the number and size of the clusters are either not fixed in advance or are difficult to manage. The proposed algorithm in MCDA has successfully overcome the issues offered by centralized and distributed cluster designing techniques through its multilayered probabilistic cluster designing approach.

This results in minimum energy consumption during the cluster designing process that ultimately increases the network life time. Neighbor Counter, Decision-Maker Node and packet sequence Id with postfix counter are the key factors in designing the clusters. Neighbor Counter works for preferring one node over others for selection of various positions (decision maker, cluster head) at various steps. Decision-Maker Nodes play their role for selection of cluster heads from the subsequent layer and packet sequence Id with postfix counter acts to group the nodes and to prefer one node over others from that group for becoming CH.

Second layer nodes ($Node_{L_2}$) elect the node with highest node density (node degree) as their decision maker node ($Node_{(dm)}$), i.e., $Cnt_{n_i} > Cnt_{n_j} \forall_i$ and $j = 1,2,3, \dots, n$ and n is equal to all nodes with same sequence number belonging to same group. $Node_{L_2}$ communicate their nodal density (Cnt_{n_i}) on their turn to their $Node_{(dm)}$ to take part in competition of becoming CH. Time slots are assigned to these nodes based on Time Division Multiple Access (TDMA) technique (Line 1 to Line 8 of Algorithm 2). A Sample example is given in subsequent paragraphs along with Table 3 in its support. When the first node of $Node_{L_2}$ communicates its nodal density (Cnt_{n_1}) to $Node_{(dm)}$, it assigns a sequence number ($Pkt_{(Seq\_no)}$) with postfix counter '0' to this packets. All the recipient nodes of $Node_{L_2}$ save this $Pkt_{(Seq\_no)}$ and become part of the same group. All the nodes that received this packet with same $Pkt_{(Seq\_no)}$ are included in the same group. Only those nodes of a group communicate their $Cnt_{n_i}$to $Node_{(dm)}$ which have highest nodal density than their previous nodes (Line 9 to Line 20 of Algorithm 2).

These nodes increment the postfix counter with two fold advantages: i) To let the other member nodes of same group to know about their Cnt_{n_i}, ii) To let the non-member nodes to know that they should neither continue this postfix counting nor save any info of other group's member nodes. This postfix counter assists the $Pkt_{(Seq_{no})}$ in separating the members of one group from other. The node right after the last member of first group communicates to its $Node_{(dm)}$ and assigns the new $Pkt_{(Seq_{no})}$ with postfix counter '*0*'. After collecting the nodal density of the second layer's selected nodes, the decision-maker nodes elect the CH having the higher nodal density among its second layer's addressed nodes (Line 21 to Line 35 of Algorithm 2). **Figure 4.6** shows the pseudo code for MCDA function for the clustered layer.

ALGORITHM 2. Function of MCDA for Clustered Layer

Start

If *Node* $\in Node_{L_2}$ **Then**
Set_up array of $Cntr_{n_i} \in Node_{L_1}$
Compare $Cntr_{n_i} \in Node_{L_1}$
Elect $Node_{(dm)}$ *having Max* $Cntr_{n_i}$ *among* $Node_{L_1}$ *in array*
$Msg_{(reply_{n_i})} = Node_{(dm_{id})} + Cntr_{n_i}$
And
$Msg_{(reply_{n_i})}$ *has unique Id*
$Node_{L_2}$ *broadcast* $Msg_{(reply_{n_i})}$ *on allocated time slots*
If $Node_{(R_x)} \in Node_{L_2}$ **Then**
Note the $Pkt_{(Seq\_no)}$
Note the $Cntr_{n_i}$
Else If $Node_{(R_x)}$ *already has* $Pkt_{(Seq\_no)}$ **Then**
If *without postfix counter* $[Saved\_Pkt_{(Seq\_no)} = Rcvd\_Pkt_{(Seq\_no)}]$
Then
If $Rcvd\_Cntr_{n_i} > Self\_Cntr_{n_i}$ **Then**
Go to silent mode
Else
Increment Postfix counter of $Pkt_{(Seq\_no)}$
Reply on allocated time slot
End if
End if
Else if $Node_{(R_x)}$ *don't have* $Pkt_{(Seq\_no)}$ **Then**
If $Rcvd\_Pkt_{(Seq\_no)}$ *has* $Cntr_{(Postfix)}$ **Then**
Discard the packets
Else
Note the $Pkt_{(Seq\_no)}$
Note the $Cntr_{n_i}$
End if
Else if $R_{(B_{T_x})} \in Node_{L_1}$ **Then**
Compare $Node_{i(cnt)} \in Node_{L_1}$
Elect CH having Max $Cntr_{n_i}$ *among* $Node_{L_1}$ *in array*
Reply to the elected cluster head of $Node_{L_2}$
End if **End if** **End if**
Else
Discard the packet
End if
End if

End

Figure 4.6: Pseudo code — Function of MCDA for clustered layer

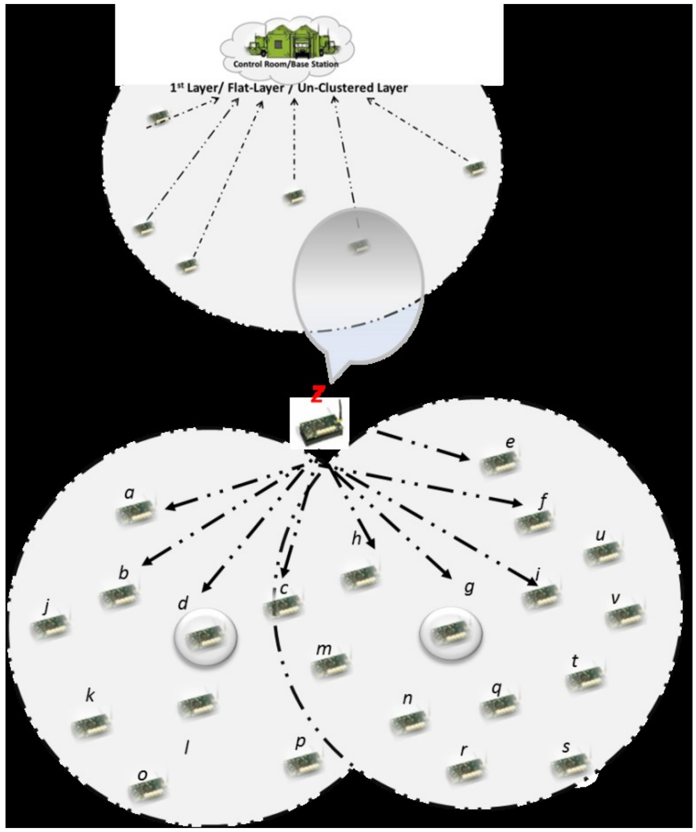


Figure 4.7: Cluster Head Selection (d, g) at Second Layer among Neighbor Nodes of Selected Node (Z) at the First Layer

The subsequent paragraphs describe the designing of clustering layers in MCDA by mapping it on a simple scenario that is also portrayed in Figure 4.7.

Let nodes *a, b, c, d, e, f, g, h, i* and j be present in the second layer, which are to reply (addressed to) node '*z*' of the first layer. The wireless medium is shared among all the second layer neighbor nodes to access node '*z*' of the first layer. These nodes use digital medium access technique, Time Division Multiple Access (TDMA). An example of assigning the time slots to these second layer nodes is tabulated in Table 4.3 along with the complete scenario of medium access and algorithmic effects on neighbors.

Table 4.3: Step 1 - Assignment of Time Slot for Broadcasting to Nodes and their effect (listener's response) on Cluster Designing

Node ID	Time Slots for Broadcasting (ms)	Reply Message Sequence #	Number of Neighbors	Listeners	Listener's Response
a	0.0 - 0.1	1	7	*b,c,d,h*	*b,c,h* will be silent
b	0.1 - 0.2	NA	5	NA (Silent)	NA
c	0.2 - 0.3	NA	6	-do-	NA
d	0.3 - 0.4	1	8	*a,b,c,h*	Already Silent
e	0.4 - 0.5	2	8	*f,g,i*	*f,i* will be Silent
f	0.5 - 0.6	2	7	NA (Silent)	NA
g	0.6 - 0.7	2	9	*e,f,i*	* *e,f* are already Silent * *i* will be Silent
h	0.7 - 0.8	1	5	NA (Silent)	NA
i	0.8 - 0.9	2	7	-do-	NA

Hence on the basis of sequence # of the received packet from the neighboring node of the second layer to node '*z*', there are two categories of nodes. In the first category, the competing nodes are *a, b, c, d,* and *h*. Among which node *d'* has the highest number of neighbors, so has been elected as cluster head while other competing nodes have been given the status cluster member. In the second category, among the competing nodes, *e, f, g* and *i,* node '*g'* having the highest number of neighbors is designated as CH and other nodes as CMs.

Table 4.4: Step 2 - Categorization of Nodes based on Sequence Number and its role in Cluster Designing

Sequence #	Competing Nodes		Decision	
	Node-ID	Number of Neighbors	CH	CM
1	a	7	d	a,b,c,h
	b	5		
	c	6		
	d	8		
	h	5		
2	e	8	g	c,f,i,e
	f	7		
	g	9		
	I	7		

4.4.4 Cluster Member Selection

The elected cluster heads broadcast "*join request*" packets (Line 1 to Line 2 of Algorithm 3). This is to inform other sensor nodes of its availability as CH. The recipient nodes send their consent message in the form of "*join accept"* message to become cluster members (Line 11 of Algorithm 3). If "join request" message is received from more than one CH, and then the recipient node sends a request message to know their number of cluster members (Line 3 to Line 7 of Algorithm 3). The decision regarding membership is based on the current load on CH, i.e., CH having less number of member nodes is preferred to send acknowledgement message for attaching with it (Line 8 to Line 9 of Algorithm 3). This helps in designing clusters with nearly equal load. Pseudo code for the cluster member selection is shown in Figure 4.8.

ALGORITHM 3. Function of MCDA for Clustered Member Selection

Start

If *Node = CH* **Then**

Broadcast $Pkt_{(join_{rqst})}$

If $Node_{(R_x)} \in Node_{L_1}$ **Then**

If $count\ \left(Pkt_{(join_{rqst})}\right) > 1$ **Then**

$Node_{(R_x)}\ Pkt_{(CM_{cnt_{rqst}})}$ *from* CH_i

CH_i *waits for specific interval*

$Pkt_{(CM_{cnt_{rply}})}$

$Node_{(R_x)}$ *Acknowledge to* CH_i *having* $CM_{(\min\_cnt)}$

Select it as its CH

Else

Reply $Pkt_{(join_{acpt})}$

End if

End if

End if

End

Figure 4.8: Pseudo code—cluster member selection

4.5 Comparative Analysis of MCDA with CCD and DCD Algorithms

We developed a simulator for WSN using C-Sharp as part of our research work. After testing the simulator for some examples, this underlying algorithm, MCDA, was implemented along with other competing algorithms. In this Section, a comprehensive discussion is made on the comparative analysis of MCDA with state-of-the-art algorithms from centralized cluster designing approach, TLPER, and distributed cluster designing approaches, EELBCRP and V-LEACH. The following performance evaluation parameters are taken into account for the comparison of the aforementioned algorithms.

- Energy Consumption
    - Energy consumption per node in cluster designing
    - Average energy consumption per node in cluster designing
    - Total network energy consumption in cluster designing

- Energy consumption in cluster designing during broadcast transmission process
- Energy consumption in cluster designing other than broadcast transmission process

- Number of packets broadcast in cluster designing process
- Number of clusters designed

Comparative analysis of competing algorithms on the above-mentioned performance evaluation parameters is depicted in different figures: Figure 4.9 to Figure 4.25.

Balanced and optimized participation of interacting network nodes during the cluster designing process has its vital role in prolonging the network life time.

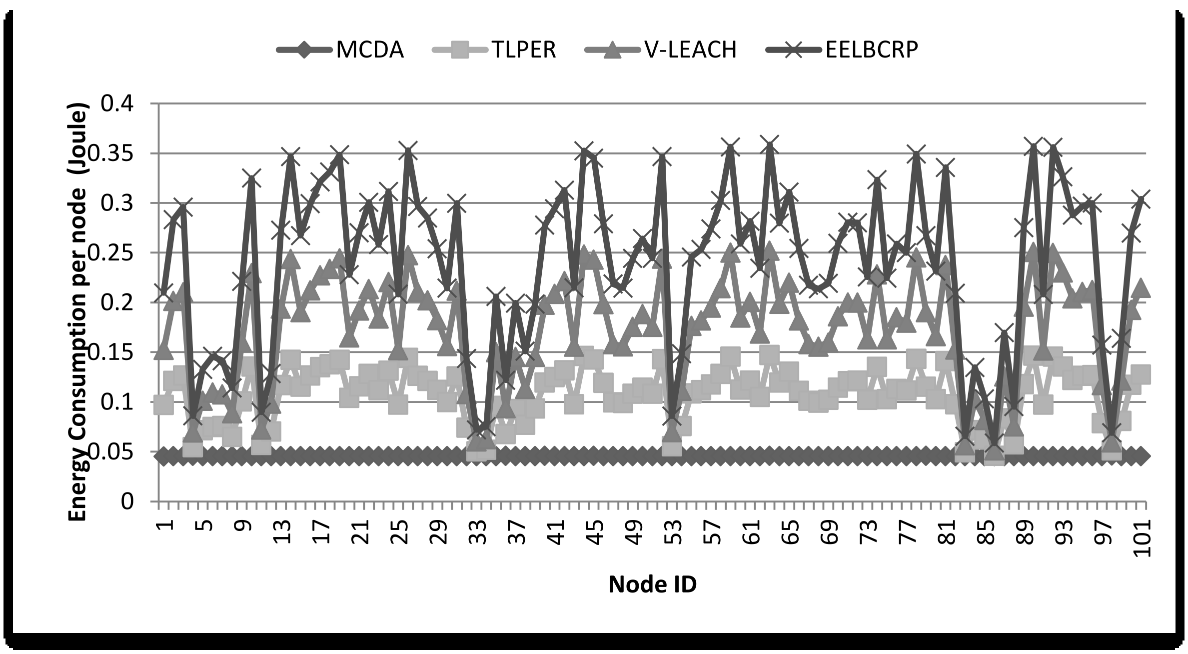


Figure 4.9: Energy Consumption per Node over Deployment Area of 100m x 100m

If some nodes contribute more actively to some of the processes while others are silent or passively participate, then it produces more opportunities for early death of some of the nodes, network partitioning and decrease in the network life time. On moving from worst to best, Figure 4.9 portrays the maximum imbalanced and non-optimized network utilization of EELBCRP compared to the other competing algorithms, TLPER, V-LEACH, and MCDA. In EELBCRP, the cluster designing process is distributed, centrally initiated from the base station and requires information of levels, upper and lower bounds and distance from the base station to compute the cluster head decision criteria. This part that requires at least two times broadcast transmission by the base station makes the cluster designing process different from V-LEACH.

This computed decision criterion is then exchanged between the neighboring nodes and hence the CHs with the most optimized values are elected. The aforementioned algorithm consumes more energy than the similarly distributed cluster designing algorithm, V-LEACH, due to greater broadcast transmission and receiving and more calculations. In the case of TLPER, less energy in the underlying process is consumed as compared to V-LEACH and EELBCRP, due to its totally centralized nature since lesser broadcast and calculation at the distributed nodes are involved in this process.

Nodal density is the decision metric for the election of CH. The nodes communicate this information to BS where necessary calculations are performed, and the decision is communicated to the deployed network nodes. The network has 100 nodes deployed in the area of 100m × 100m for which we are considering MSN. Therefore, the nodes having BS accessible to direct hop communicate their info directly to the BS and there is only one layer beyond the neighborhood of BS. The nodes of this layer communicate information of their neighbor nodes (nodal density) to the BS through the transit nodes of the first layer (neighbor nodes of BS). Hence, the energy consumption of the first layer nodes is more than that of the second layer.

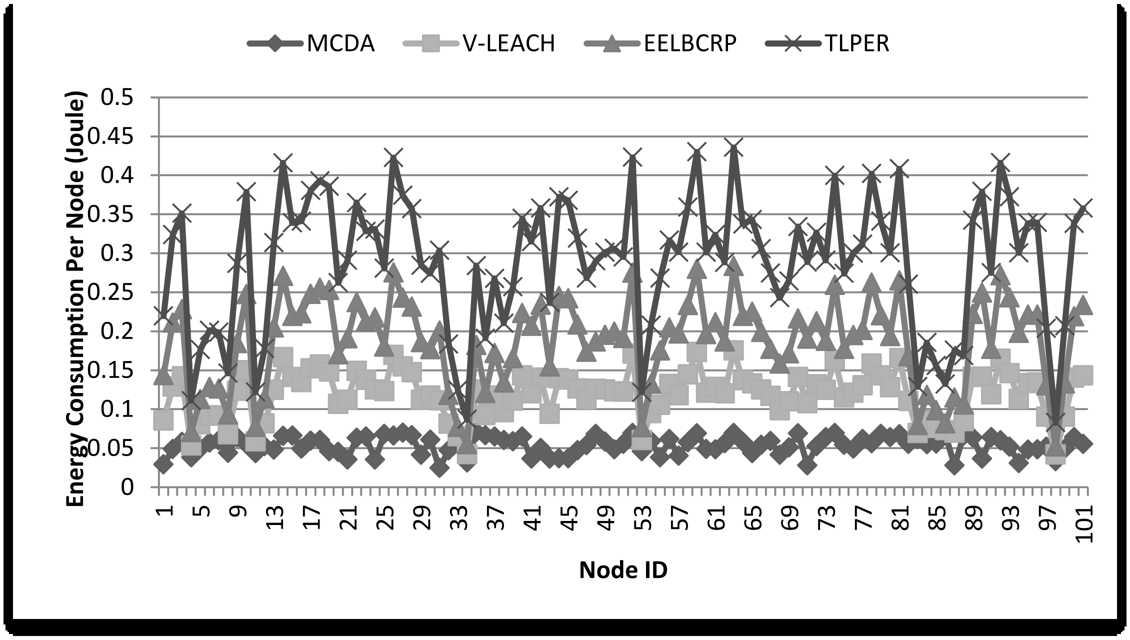


Figure 4.10: Energy Consumption per Node over Deployment Area of 200m x 200m

In larger networks, there are more intermediate layers and each layer node works as a transit for each of the subsequent layer nodes. So, more imbalanced energy consumption in such centralized strategies as compared to distributed techniques in LSN. Figure 4.10 demonstrates this effect of network scale over centralized (TLPER) and distributed (V-LEACH, EELBCRP) approaches in the energy consumption aspect during the set-up phase that becomes clearer if we compare the result of Figure 4.10 with Figure 4.9.

MCDA outperforms to other three centralized and distributed algorithms with respect to same performance evaluation metric. The listening mode of the first layer is stopped while broadcasting their nodal density to the $Node_{L_2}$ and hence the participation of $Node_{L_2}$ in the reply broadcast, transmission is also decreased much due to introduction of $P_{(Seq\_no)}$ in reply message, selective listeners' response, limited and optimized competing $Node_{(dm_{id})}$ and reduced cluster head candidates. These factors play a vital role in lessening the overall energy consumption. The flooded message broadcasting and blind inter-node message exchange of centralized and distributed cluster designing approaches are avoided in MCDA resulting in the best performance among all. In LSN with the same number of 100 nodes deployed in a 200m×200m area, per node and overall energy consumption of MCDA is improved more than the competing algorithms due to its novel centrally initiated distributed nature. TLPER goes down in performance in LSN due to more involvement of transient nodes in communicating information of distant nodes to the BS. While V-LEACH and EELBCRP gain value in energy consumption performance because of no such issue of extra work of network nodes on a large scale. In usual cases and such scenarios, the network scale does not affect much such distribution nature cluster designing algorithms. Here we have calculated the standard deviation using "n" method with the formula $\sqrt{\frac{\sum(x-\bar{x})^2}{n}}$. In TLPER, the network scale is directly proportional to the energy consumption. While in the case of the proposed algorithms MCDA network scale is inversely proportional to the energy consumption.

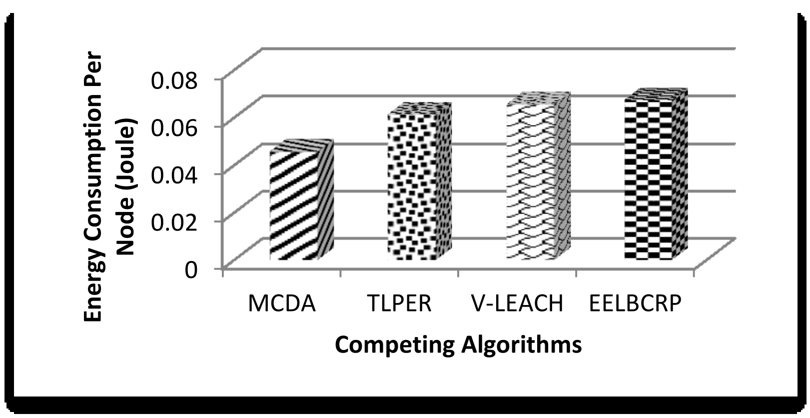


Figure 4.11: Per Node Average Energy Consumption over Deployment Area of 100m x 100m

Balanced network utilization means that all the deployed network nodes are participating in some function almost equally have a better impact on the network and save it from partitioning. Another aspect of this balanced network utilization is the level of per node energy consumption.

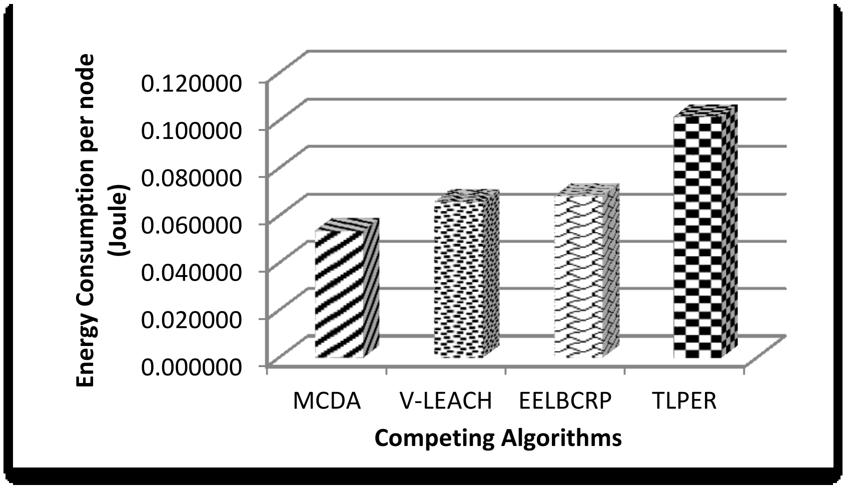
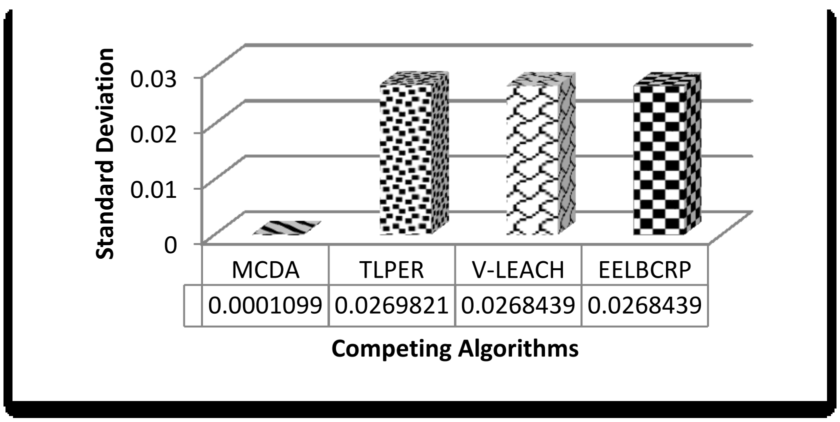


Figure 4.12: Per Node Average Energy Consumption over Deployment Area of 200m x 200m



MCDA	TLPER	V-LEACH	EELBCRP
0.0001099	0.0269821	0.0268439	0.0268439

Figure 4.13: Standard Deviation of Per Node Energy Consumption over Deployment Area of 100m x 100m

Higher energy consumption leads to squeezing the network life time. Figure 4.9 and Figure 4.10 show the aforementioned later point of minimum per node energy consumption of

MCDA as compared to other algorithms, while the first point of balanced network utilization is elucidated from Figure 4.11, Figure 4.12, Figure 4.13, and Figure 4.14.

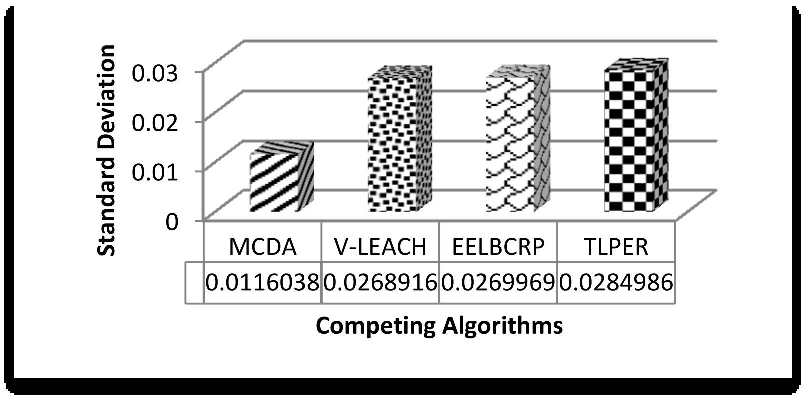


Figure 4.14: Standard Deviation of Per Node Energy Consumption over Deployment Area of 200m x 200m

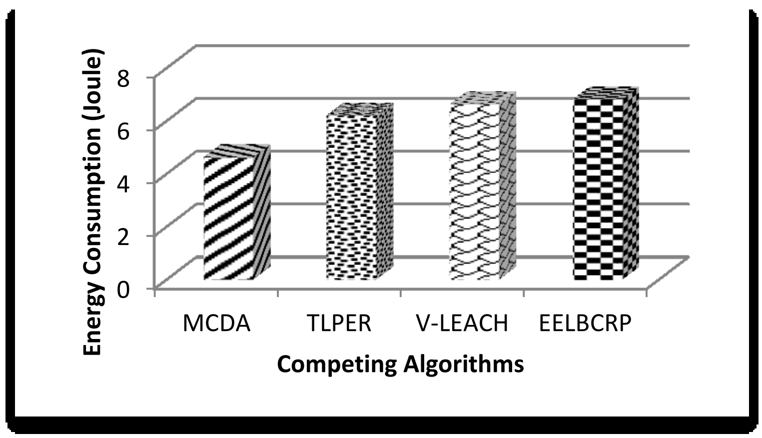


Figure 4.15: Total Energy Consumption during Cluster Designing over Deployment Area of 100m x 100m

Figure 4.15 and Figure 4.16 give an enhanced backing of our claim of optimized balanced network utilization of MCDA as compared to the other three competing algorithms. The hybrid solution proposed in MCDA gives far better performance as compared to two well-known available categories of distributed and centralized cluster designing algorithms with respect to the said evaluation parameters. This conclusion can be easily gained by combining the extracted intuitions from Figure 4.11, Figure 4.13, and Figure 4.15.

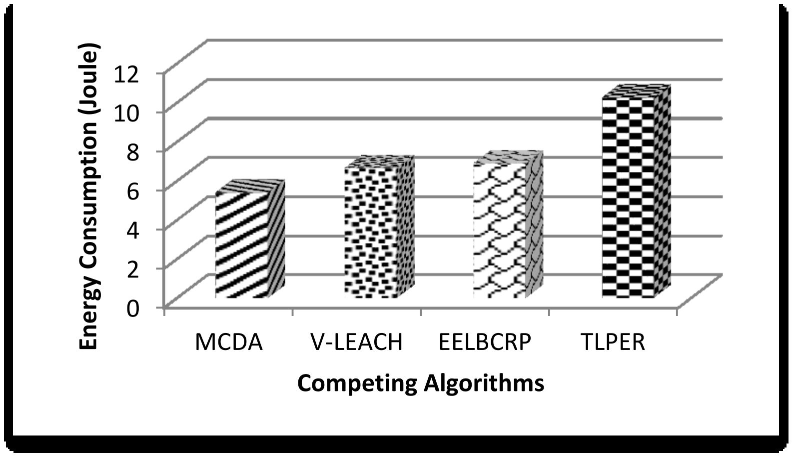


Figure 4.16: Total Energy Consumption during Cluster Designing over Deployment Area of 200m x 200m

The other graphs of same evaluation parameters in large-scale deployment area designate MCDA at a higher performance level. The CCD approach is best for the most appropriate cluster head election and selection of its members, due to centralized decision making and less inter-node communication with minimum computation. However, this advantage of CCD can only be exploited in small-scale network where the deployed network nodes can directly communicate with the base station without involvement of transit nodes. In the case of MSN, the base station is not in the footprint of distantly deployed nodes. For these nodes to communicate with the bases station, transit nodes are required to make it possible. This results in either flooding the network or finding a route from the source node to the base station to communicate the required information. In the case of LSN, this scenario becomes more severe due to involvement of more transit nodes between the source node and the target base station. Our simulated scenario considered for CCD is of medium scale since transit nodes/intermediate nodes are involved when distant nodes approach the BS. So, communication in the broadcasting fashion is an increasing factor of the deployed network scale in CCD. Figure 4.17, and Figure 4.18 are backing up our claim by showing that number of packets' broadcast by typical CCD algorithm (TLPER) are 36 % higher in MSN and 32 % in LSN compared to MCDA.

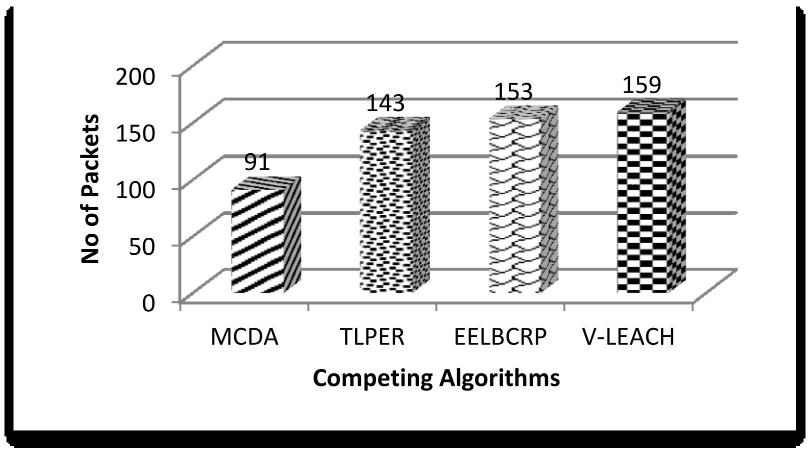


Figure 4.17: Number of Packets Broadcast during Cluster Designing over Deployment Area of 100m x 100m

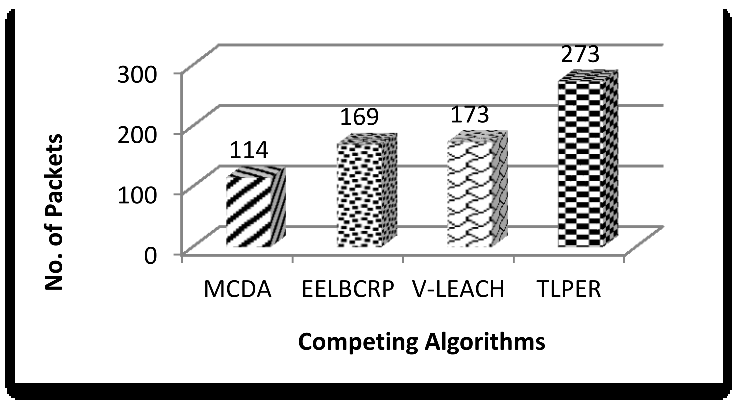


Figure 4.18: Number of Packets Broadcast during Cluster Designing over Deployment Area of 200m x 200m

Network scale has little effect on DCD approach as is elucidated from the comparative graphs in Figure 4.17, and Figure 4.18. The number of packets broadcast in LSN is 8%higher in V-LECH and 9%higher in EELBCRP compared to the number of packets broadcast in MSN that is far less than TLPER (CCD). Although there is 20% marginal increase of performance evaluation parameter for MCDA in LSN compared to MSN, MCDA is better in performance by 33, 34 and 58% compared to EELBCRP, V-LEACH and TLPER, respectively, as shown in Figure 4.19. Moreover, the number of packets broadcast in V-LEACH is slightly higher than the same strategy follower, EELBCRP. The election of Vice Cluster Head (VCH), due to which the protocol is given the name V-LEACH, is the reason for these extra broadcasts.

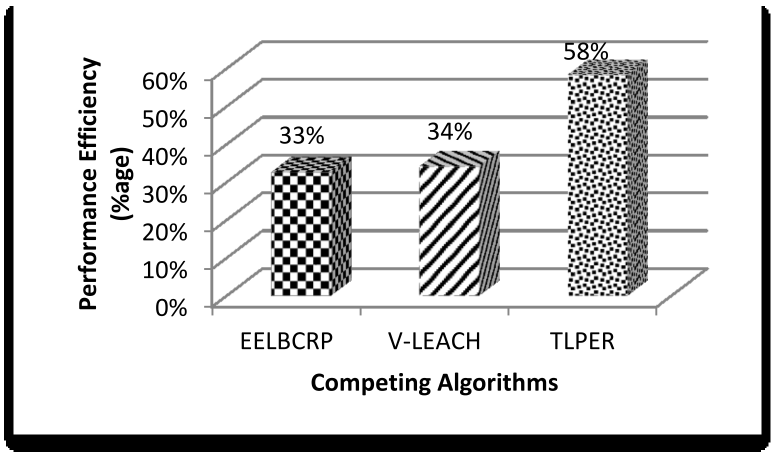


Figure 4.19: Performance Efficiency of MCDA in Energy Consumption during Broadcast Transmission with respect of Competing Algorithms in deployment Area of 200m x 200m

Figure 4.17, Figure 4.18, and Figure 4.19 regarding the number of broadcasted packets involved in network design can be interpreted as follows.

The packet broadcast in DCD compared to this effect in CCD is very few LSN. In the case of CCD, the number of packets broadcast is the increasing factor of network scale. The performance of MCDA is best as compared to both the cluster designing categories, centralized and distributed, due to the aforementioned reasons discussed in detail in the previous paragraphs. The to and fro exchange of nodal density information between $Node_{L_1}$ and $Node_{L_2}$ is the main source of packet broadcast. The election of $Node_{(dm_{id})}$, defining the threshold level in response to $Node_{(dm_{id})}$ and the introduction of $P_{(Seq\_no)}$

decrease the participating nodes to a very low level in the cluster designing process resulting in less packet broadcasting as compared to the other three competing algorithms.

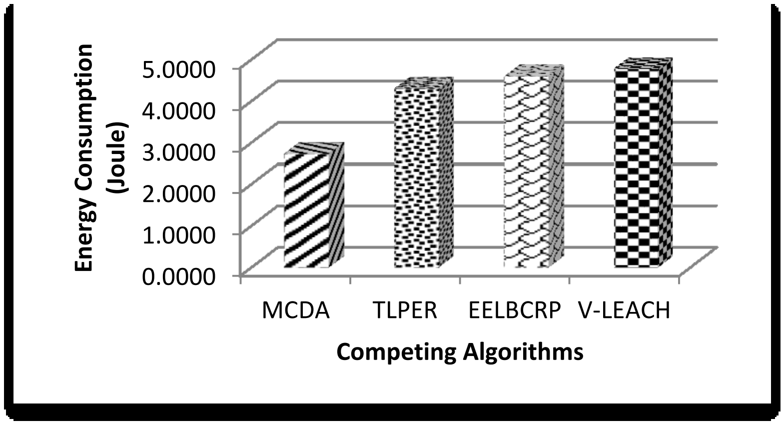


Figure 4.20: Energy Consumption in Broadcast Transmission during Cluster Designing over Deployment Area of 100m x 100m

On mapping the packet broadcasting effect over the energy consumption during cluster designing process, it is simply concluded from Figure 4.20, and Figure 4.21 that performance of MCDA is better both in MSN and LSN as compared to CCD and DCD.

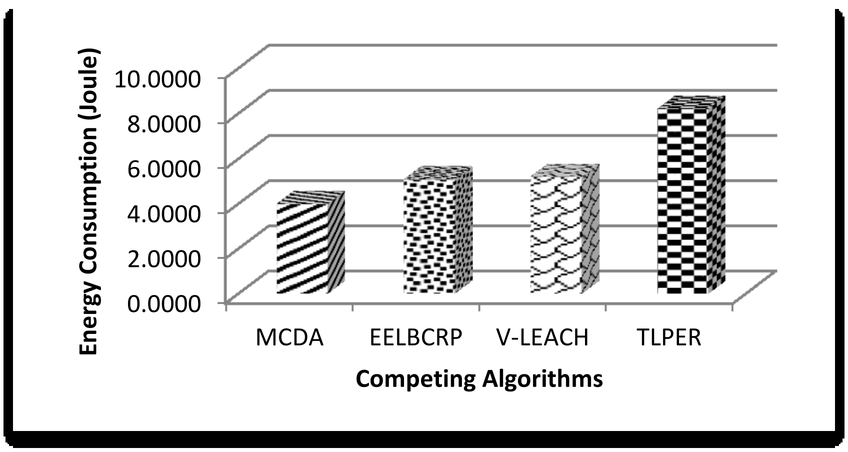


Figure 4.21: Energy Consumption in Broadcast Transmission during Cluster Designing over Deployment Area of 200m x 200m

Unicasting and unicast message reception and computation are some of the energy consumption factors that are considered in the network domain other than packet broadcasting. We have also evaluated the performance of competing algorithms on the basis of energy consumption during cluster designing other than broadcast transmission (energy consumption in all processes involved in cluster designing, say reception, processing, etc.).

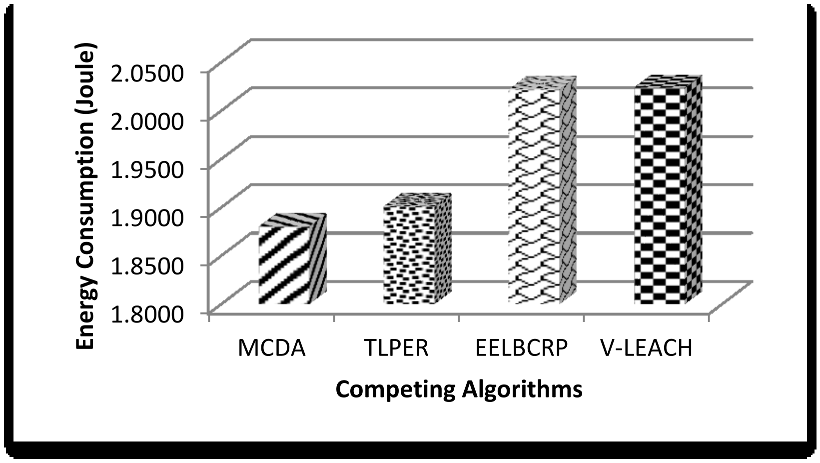


Figure 4.22: Energy Consumption other than Broadcast Transmission during Cluster Designing over Deployment Area of 100m x 100m

Figure 4.22, and Figure 4.23 represent the comparative analysis of these algorithms. Further on comparing these figures, it can be noticed that the energy consumption during the cluster designing process other than broadcast transmission process in the LSN is lesser than that of MSN in MCDA, EELBCRP and V-LEACH, while in the case of TLPER it is slightly higher. In the former case, the number of packets broadcast is higher in the deployment area of 200m ×200m compared to that of 100m×100m.

Moreover, more broadcast packets mean more nodes will potentially be involved in the broadcast reception, so the algorithm that broadcasts more packets also has a higher number of nodes involved in the reception of these broadcasted packets

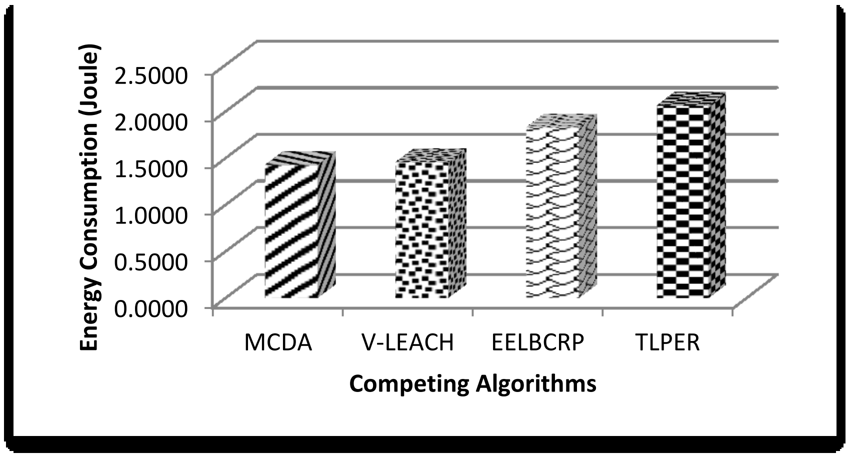


Figure 4.23: Energy Consumption other than Broadcast Transmission during Cluster Designing over Deployment Area of 200m x 200m

Figure 4.24, and Figure 4.25 add their conclusions to finding the answers of the said point. Number of designed clusters in LSN compared to MSN with the same number of 100 nodes shows that nodes are sparsely deployed. So, less nodal density means that less number of nodes act as the recipient nodes of any single broadcast. This sparse deployment also has its effect on the number of broadcast packets as shown in Figure 4.17, and Figure 4.18, but the underlying algorithm, MCDA, has a dominant role that can be seen from the comparative study of these figures. In the latter case of TLPER, each broadcasted packet recipient node further broadcasts the received information until it reaches BS. Also, the number of broadcast packets in LSN is about 48% higher than MSN. So, in view of the highlighted two points, it seems to be very logical that the number of recipient nodes of broadcasted packets is higher in LSN compared to MSN.

In continuation of this, the effect of sparse deployment can be noticed from comparison of Figure 4.23 with the Figure 4.22 which shows only 8% increase in the energy consumption in LSN in contrast to 48% increase in the broadcast packets in LSN.

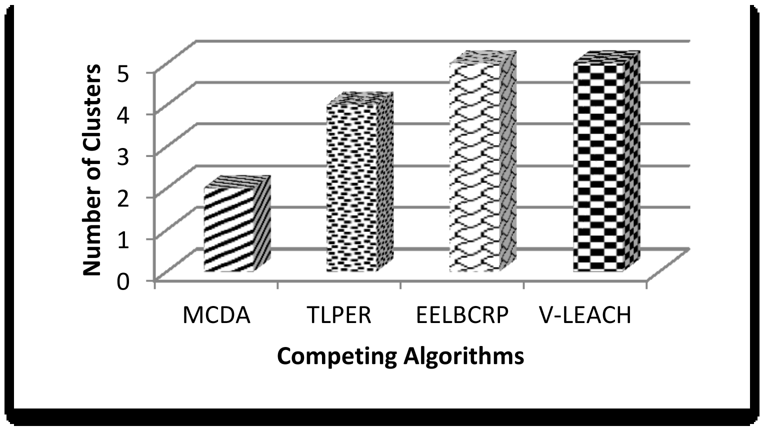


Figure 4.24: Number of Clusters Designed in the deployment of 100 Nodes in the area of 100m x 100m

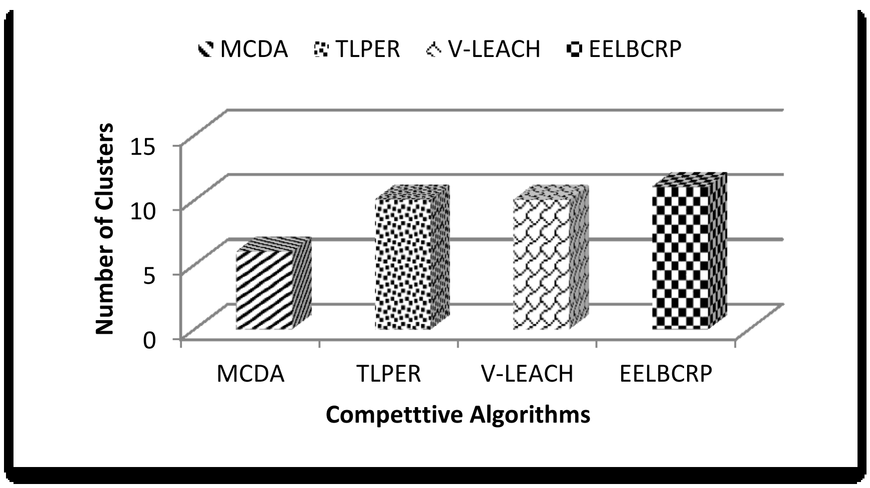


Figure 4.25: Number of Clusters Designed in the deployment of 100 Nodes in the area of 200m x 200m

4.6 Extended MCDA

In a continuation of proposed idea presented in Section 4.4 on energy efficient cluster designing, a constructive ramification of this idea is proposed with the name Extended MCDA (E-MCDA) to ameliorate the performance in network life time. Novel algorithms for time slot allocation, minimizing the CH competition candidates, and cluster member selection to CH play underpinning roles to achieve the target. These incorporations in MCDA result in minimizing transmissions, suppressing unneeded response of transmissions and near equal size and equal load clusters. We have done extensive simulations in NS2 and evaluate the performance of E-MCDA in energy consumption at various aspects of energy, packets transmission, number of designed clusters, number of nodes per cluster and un-clustered nodes. It is found that the proposed mechanism optimistically outperforms the competition with MCDA and EADUC. More-over, the assumptions made for homogeneity of nodes, communication radius model, reliability of the communication link, communication neighbor set and network nodes are same as are explained in Section 4.2.

The figures from Figure 4.26 to Figure 4.34 and the tables from Table 4.5 to Table 4.9 show the working of the extended version. Time slot allocation at network setup phase is introduced to make the cluster designing process more energy efficient in Section 4.6.1, energy efficient cluster head selection idea is explained in Section 4.6.2, 'Required Node Degree' based cluster member selection for near equal size clusters is given in Section 4.6.3. Section 4.7 discusses the comparative analysis of Extended MCDA with MCDA and another state-of-the-art cluster designing algorithm.

4.6.1 Time Slot Allocation at Network Setup Phase

The proposed improvement of introducing the time slot allocation at network setup phase minimizes the message broadcast during selection of $Node_{(dm)}$. It also has its role in the election of cluster heads by suppressing the turns of nodes with equal and lower degree to take part in said processes since the decision for the same is based on the highest node degree. This step is the extension of work presented in Section 0 to make the cluster designing process more energy efficient.

All network nodes broadcast beacon message ($Msg(Beacon)$) that is piggybacked with the information of their number of neighbors. With this all recipient nodes including BS set up their neighbor table containing Node id and No. of neighbors (Line 1 to Line 4 of Algorithms 4). BS broadcasts initialization message ($Msg_{(setup_{init})}$) to initiate the cluster designing process. Recipient nodes are designated as first layer nodes($Node_{L_1}$) (Line 5 to Line 7 of Algorithm 4). $Node_{L_1}$send their number of neighbors excluding their neighbors that are not from $Node_{L_1}$ i.e. $Nodes_{(rem)}$ (Line 8 to Line 13 of Algorithm 4). Now the BS assigns the node Ids to $Node_{L_1}$ according to their $Nodes_{(rem)}$ value (Line 14 to Line 16 of Algorithm 4). Total time slots allocated to the $Node_{L_1}$ i.e. ($Total_{TS}$) is calculated by BS as given in Equation 3, Equation 4 and Equation 5 (Line 17 to Line 20 of Algorithm 4).

$$\Delta \boldsymbol{t_i} = \Delta t_{i-1} + \Delta t \qquad (3)$$

$$\Delta t = \left(T_{est_{tx}} + T_{GI}\right) \qquad (4)$$

$$Total_{TS} = \sum_{i=1}^{n} \Delta t_n + \Delta t \qquad (5)$$

Now ultimately, BS broadcasts flat layer initialization message ($Msg_{(FL_{init})}$) to formally initiate the designing of clustered network. $Msg_{(FL_{init})}$ contains $Total_{TS}$, Δt and newly allocated $Node_{ids}$ (Line 21 and Line 22 of Algorithm 4). Recipient nodes of $Msg_{(FL_{init})}$calculate $T_{wait(t_i)}$ as in Equation 6 (Line 23 to Line 25 of Algorithm 4).

$$T_{wait(t_i)} = Total_{TS} - \Delta t_i \text{ or } Total_{TS} - (\Delta t \times i) \qquad (6)$$

To initiate the clustering process in the second layer nodes ($Node_{L_2}$), clustering layer initialization message ($Msg_{(CL_{init})}$) that has the information of $T_{wait(t_i)}$ and Cnt_{n_i} is broadcasted. Only $Node_{L_2}$ receive the packet and all other nodes that are of $Node_{L_1}$ discard the packet (Line 26 and Line 32 of Algorithm 4).

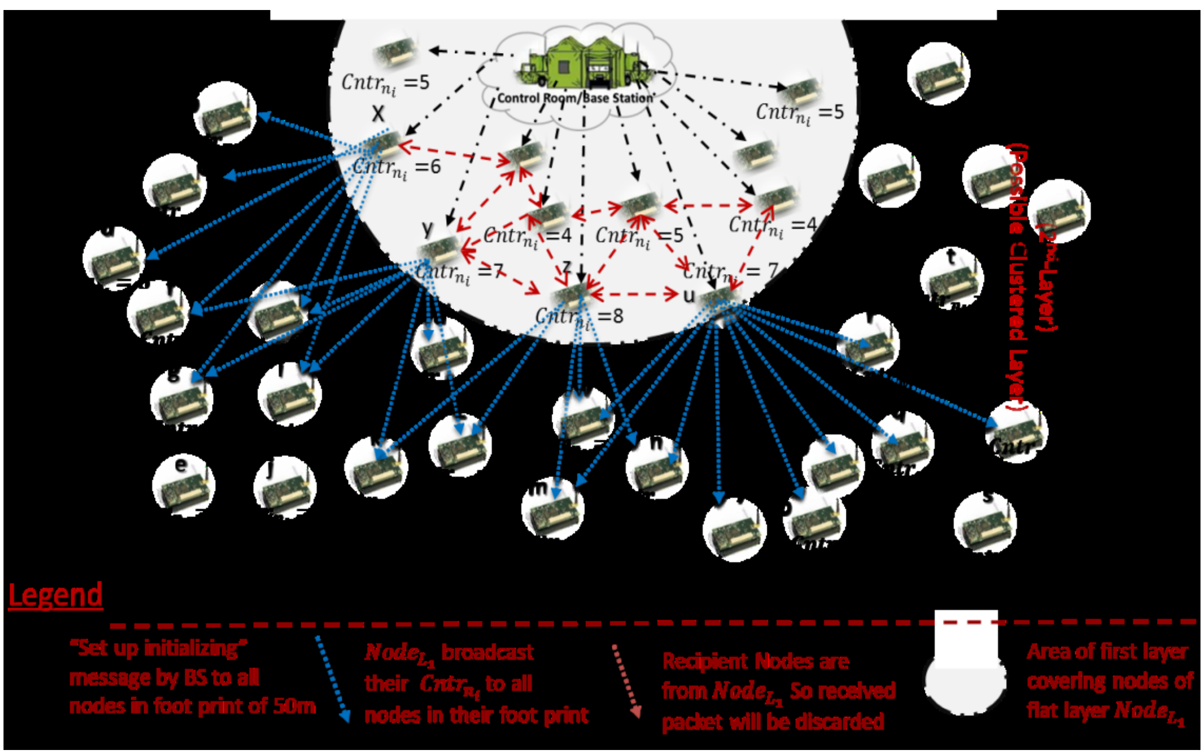


Figure 4.26: Formation of First Layer

Refer to the Figure 4.26, there are 11 nodes in footprint of BS to receive this message and are comprising of the first layer. $Msg_{(FL_{init})}$ message consists of 128 bits and transmission time for a packet is $128\mu s\ per\ packet(message)$. If Δt is the time slot allocated to a node which consists of estimated transmission time $T_{est_{tx}}$ and the safe gap in the transmission of next node called guard interval T_{GI} then first node from $Node_{L_1}$ is allocated Δt_1 that is equal to Δt as in Equation 7.

$$\Delta t = \left(T_{est_{tx}} + T_{GI}\right) = (128 + 25)\mu s = 153\mu s \qquad (7)$$

The next allocated time starts right after the completion of this Δt_1 and so on.

Calculation for the same is given as follows based on $\Delta t_i = \Delta t_{i-1} + \Delta t$:

Let $i = 1$ and $\Delta t_0 = 0$,

So, $\Delta t_1 = \Delta t_0 + \Delta t = 153\mu s$,

If $i = 2$ and $\Delta t_1 = 153\mu s$, Then $\Delta t_2 = \Delta t_1 + \Delta t = (153 + 153)\mu s = 306\mu s$

If $n = i$ and $\Delta t_1 = 306\mu s$, Then $\Delta t_3 = \Delta t_2 + \Delta t = (306 + 153)\mu s = 459\mu s$

.
.
.

Similarly,

If $i = 10$ and $\Delta t_1 = 1377\mu s$, Then $\Delta t_{10} = \Delta t_9 + \Delta t = (1377 + 153)\mu s = 1530\mu s$

and If $i = 11$ and $\Delta t_1 = 1530\mu s$, Then $\Delta t_{11} = \Delta t_{10} + \Delta t = (1530 + 153)\mu s = 1683\mu s$

ALGORITHM 4. Function of E-MCDA for Flat Layer

START

$Node_{all}$*broadcasts* $Msg(Beacon)$
$Node_{all}$*Setup* $Table_{(nbr)}$
BS Setup $Table_{(nbr)}$
$R_{(B_{T_x})}$ *= 100m*
$Msg_{(setup_{init})}$*Contains* N_Cnt_{BS}
BS broadcast $Msg_{(setup_{init})}$
Set $Node_{(R_x)} = Node_{L_1}$
$Node_{(Rx)}$*Calculates*$Nodes_{(rem)}$
    If $Node_{id}\ [BS(Table_{(nbr)})] = Node_{id}\ [Nodes(Table_{(nbr)})]$ ***Then***
        $Cnt_{(node)}++$
    End if
$Nodes_{(rem)} = [\,Nodes(Table_{(nbr)}) - Cnt_{(node)}]$
$Node_{(Rx)}$ *Sends* $Nodes_{(rem)}$ *to BS*
BS Generates $List(Tx_{seq})$ *Based on* $Nodes_{(rem)}$
Sort $List(Tx_{seq})$ *in ascending order*
Allocate $Node_{ids}$*to nodes based on their values in sorted* $List(Tx_{seq})$
BS calculates$Total_{TS}$
$\Delta t = \left(T_{est_{tx}} + T_{GI}\right)$
$\Delta t_n = \Delta t_{i-1} + \Delta t$
$Total_{TS} = \sum_{i=1}^{n} \Delta t_n + \Delta t$
$Msg_{(FL_{init})}$ *contains* $Total_{TS}$, Δt *and newly allocated*$Node_{ids}$-
BS broadcasts$Msg_{(FL_{init})}$
$Node_{(Rx)}$ *calculate* $T_{wait(t_i)}$
$\Delta t_i = (\Delta t \times i)$
$T_{wait(t_i)} = Total_{TS} - \Delta t_i$
$Msg_{(CL_{init})} = T_{wait(t_i)} + Cnt_{n_i}$
$Node_{L_1}$ *Broadcast* $Msg_{(CL_{init})}$
Set Transceiver of $Node_{L_1}$ *= Sleep mode for specific time interval*
    If $recipients\left[Msg_{(CL_{init})}\right] \notin Node_{L_1}$ **Then**
        Receive the packet
        Set $Node_{(R_x)} = Node_{L_2}$
    End if

End

Figure 4.27: E-MCDA Function for Flat Layer

Hence based on the above calculations, total transmission time $Total_{TS}$ of first layer nodes having 11 nodes in number is $1683\mu s$ i.e. $(128\mu s + 25\mu s) \times 11$.

$$Total_{TS} = (128\mu s + 25\mu s) \times 11 = 1683\mu s$$

Since BS knows the number of nodes in the first layer as is discussed previously. So this all calculation of $Total_{TS}$ of first layer nodes is performed by BS and is piggybacked in $Msg_{(FL_{init})}$ message to be sent to nodes of first layer. We are in a plan that all the $Node_{L_2}$ must not participate in the competition of being CH in order to lessen the broadcasting since the CH announcement of highest degree node suppresses the broadcasting of node with equal and lower degree node. Moreover there is not any possibility that lower degree node may announce its candidacy of being CH before the higher degree nodes and both these nodes are in the communication range of each other.

For the said purpose, each node calculates $T_{wait(t_i)}$ that is equal to $Total_{TS} - \Delta t_i$. Sample calculation for the same is also performed in subsequent paragraphs.

Let $Total_{TS} = 1683$ and $i = 1$

If $\Delta t_1 = 153\mu s$ Then $T_{wait(t_1)} = 1683\mu s - 153\mu s = 1530\mu s$

If $\Delta t_2 = 306\mu s$ Then $T_{wait(t_2)} = 1683\mu s - 306\mu s = 1377\mu s$

If $\Delta t_3 = 459\mu s$ Then $T_{wait(t_3)} = 1683\mu s - 459\mu s = 1224\mu s$

.

.

.

Similarly,

If $\Delta t_{11} = 1683\mu s$ Then $T_{wait(t_{11})} = 1683\mu s - 1683\mu s = 0\mu s$

We can have a look over the calculated values of Δt_n, and $T_{wait(t_i)}$ from the succeeding process. We notice that the output is in the increasing order in case of Δt_n and in decreasing order in case of $T_{wait(t_i)}$. This is also depicted in part 'a' and part 'b' of Figure 4.28.

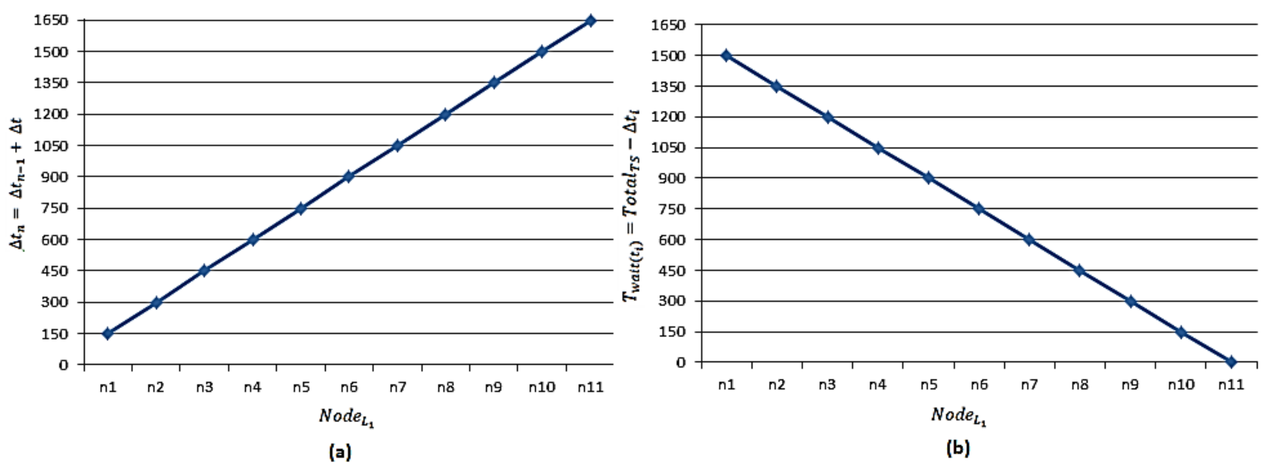


Figure 4.28: Depiction of calculation of Δt_n *and* $T_{wait(t_i)}$

$Node_{L_1}$ broadcast this calculated value of $T_{wait(t_i)}$ along with Cnt_{n_i} to $Node_{L_2}$ in $Msg_{(CL_{init})}$ for further calculation of $T_{net_{wait}}$ for assigning the turns of second layer nodes to take part in selection of decision maker nodes ($Node_{(dm)}$) and later on in CH election. Hence based on the above mentioned discussion, all the $Node_{L_2}$ are at same level to be in fair competition of being CH. The subsequent layers are defined on the basis of transmission range of previous layer nodes (first layer nodes in this case till now). Figure 4.26 shows this layered representation of the deployed nodes and summarized description in the form of legend on formation of first layer. Figure 4.27 gives pseudo-code for the function of E-MCDA at flat layer.

We started the network clustering from the second layer up to the network boundary. The cluster heads in the second layer are selected by the elected decision maker nodes of the first layer. This saves energy that other cluster based routing algorithms consume for frequent cluster designing in the neighborhood of the base station (as in DSS algorithms) or re-clustering of the whole network (as in centralized cluster based networks). This also decreases the load on the neighbor nodes that ultimately does the load balancing and hence increases the life time of network. After setting up of first layer, $Node_{L_1}$ play their role for the designing of second layer; clustered layer. Extended MCDA designates decision maker nodes from $Node_{L_1}$to break the conflict of claim of nodes for heading the nodes in its neighbors. $Node_{L_1}$broadcast $Msg_{(CL_{init})}$ message with the fields $Cntr_{n_i}$(their node degree) and $T_{wait(t_i)}$ (time for which the $Node_{(Rx)_i}$of $Msg_{(CL_{init})}$ message must wait before it takes any action) values for the initialization of cluster designing process at second layer. The suggested improvements in designing of second layer presented in Section 4.4.3 is discussed in detail in subsequent sub section along with brief shortcomings of other two competing cluster designing methods.

4.6.2 Energy Efficient Cluster Head Selection

Extended MCDA is introducing a new ever technique for designing the clusters by sensibly managing the announcement of being CH in a distributed way. Neighbor Counter and Decision Maker Node are the key factors in designing the clusters. Where neighbor counter is for preferring one node over others for selection of various positions (decision maker, cluster head) at various steps, and Decision Maker Node is for the selection of cluster head from the subsequent layer (especially in case of tie). The cluster designing process at second layer is initialized with the $Msg_{(CL_{init})}$message by $Node_{L_1}$. Its recipients that are not from $Node_{L_1}$ comes in second layer and are called second layer nodes ($Node_{L_2}$). These nodes set up their array of neighbor count of first layer nodes and compared them. Among those, the node which has the highest neighbor count ($Max\ Cnt_{n_i}$)is elected as decision maker node ($Node_{(dm)}$) (Line 1 to Line 4 of Algorithm 5). Recipients of $Node_{L_2}$ start their timers as soon as they receive this message and set it to $T_{wait(t_i)}$ whose value is set by the $Msg_{(CL_{init})}$ message sent from $Node_{L_1}$. A node may receive $Msg_{(CL_{init})}$ message from more than one $Node_{L_1}$. In this case only the first $T_{wait(t_i)}$ value is considered and all others' are ignored. $T_{wait(t_i)}$ value is different for different $Msg_{(CL_{init})}$ messages recipient groups (Line 5 to Line 10 of Algorithm 5).

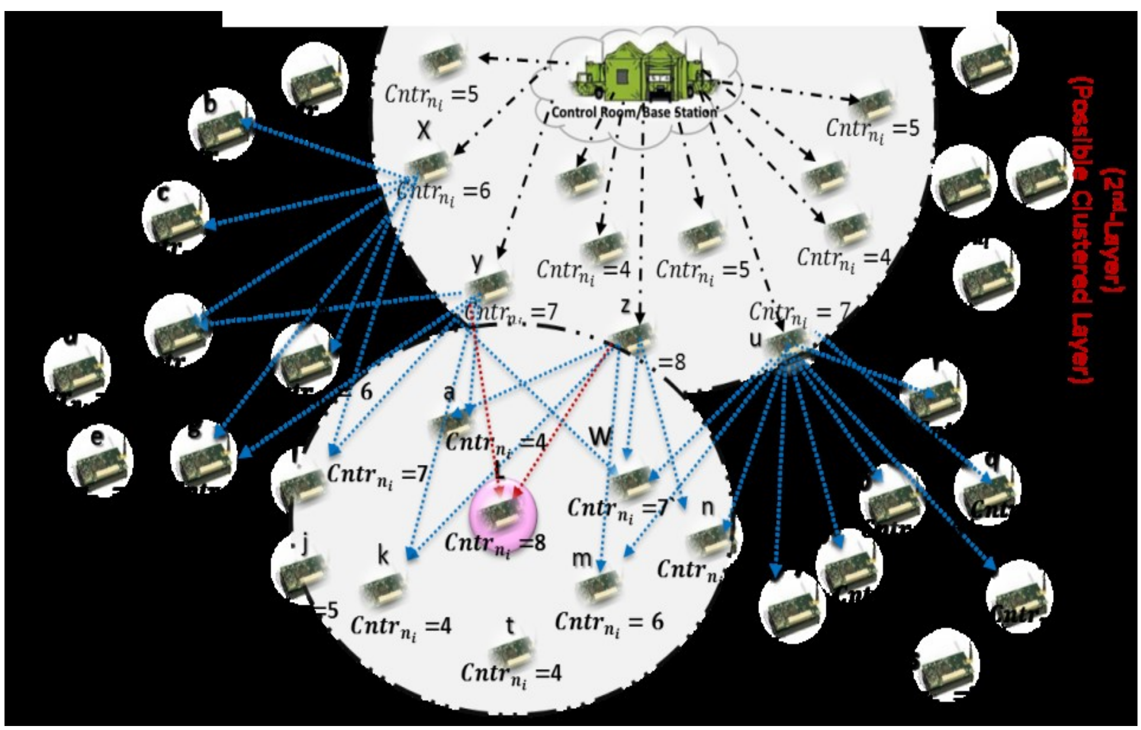


Figure 4.29: Election of first cluster head in 2nd Layer

Line 11 to Line 13 of Algorithm 5 give an abstract level calculation of $T_{net_{wait}}$. For having more practical exposure for the aforementioned proposed solution, following example is demonstrated in detail with its depiction in Figure 4.29.

Let in a scenario, nodes $Y, Z, and\ U$are selective nodes from first layer with $T_{wait(t_y)} = 1200, T_{wait(t_z)} = 750$, and $T_{wait(t_u)} = 450$. $Msg_{(CL_{init})_y}$ message from node Y is received by f, g, i, k, l, a, w and the a, k, l, w, m, n nodes receive $Msg_{(CL_{init})_z}$ message from node Z. While the recipients of $Msg_{(CL_{init})_u}$ message from node $U$are n, y, p, o, r, q, v. Referring to Table 4.5, Node ids in bold are the nodes those are receiving $Msg_{(CL_{init})}$ messages from more than one first layer nodes. The node Y among nodes $Y, Z, and\ U$ is the first node to broadcast its $Msg_{(CL_{init})}$message followed by node $Z$and then node U. All the recipients of $Msg_{(CL_{init})_y}$message from node Yhave their $T_{wait(t_y)}$ equal to $1200\mu s$and of node Z have their $T_{wait(t_z)}$ equal to $750\mu s$.

Table 4.5: Representation of$Msg_{(CL_{init})}$ messages by $Node_{L_1}$recipients nodes from $Node_{L_2}$

Selected Nodes from $\boldsymbol{Node_{L_1}}$	Waiting time for group of recipient nodes of $Msg_{(CL_{init})}$message $T_{wait(t_i)}$	$Msg_{(CL_{init})}$message recipient nodes' group
Y	$1200\mu s$	$f, g, i, \boldsymbol{k}, \boldsymbol{l}, \boldsymbol{a}, \boldsymbol{w}$
Z	$750\mu s$	$\boldsymbol{a}, \boldsymbol{k}, \boldsymbol{l}, \boldsymbol{w}, \boldsymbol{m}, \boldsymbol{n}$
U	$450\mu s$	$\boldsymbol{w}, \boldsymbol{m}, \boldsymbol{n}, y, p, o, r, q, v$

In case of recipients of $Msg_{(CL_{init})}$ messages from node U, $T_{wait(t_u)}$ is equal to $450\mu s$. Node receiving $Msg_{(CL_{init})}$ messages from more than one first layer nodes have their $T_{wait(t_i)}$ equal to that from which it receives $Msg_{(CL_{init})}$ messages in first. Tabular representation of this scenario is demonstrated in Table 4.5. Table 4.6 demonstrates second layer nodes in separate in given scenario that is also depicted in Figure 4.29 which are at the intersection of communication range of $Msg_{(CL_{init})}$ messages from more than one first layer nodes.

Table 4.6: Representation of $Node_{L_2}$ that receive multiple $Rqst_{DM_{Elec}}$ messages from $Node_{L_1}$

Nodes receiving $Msg_{(CL_{init})}$ messages from	
$Y, and\ Z$	$Z, and\ U$
k, l, a, w	w, m, n

So, each node from $Node_{L_2}$waits for $T_{wait(t_i)}$ time received in $Msg_{(CL_{init})}$messages.This equalizes the waiting time of all $Node_{L_2}$to take any action ahead to cluster designing process. So, after finishing first layer nodes' transmission i.e. completion of $1683\mu s$ as is calculated in previous example, the first node that broadcasts $Msg(Rply_{DM_{Elec}})$ message in response of $Msg_{(CL_{init})}$ message is the node having its $Net_{Cnt_{n(i)}}$value highest among $Node_{L_2}$ i.e. also has the lowest $T_{net_{wait}}$ value (Line 14 to Line 15 of Algorithm 5).

Table 4.7: Calculation for Net Waiting Time $T_{net_{wait}}$ for $Node_{L_2}$ for energy aware designing of clusters at 2nd Layer (the node having the lowest net node degree $Net\_Cnt_{n(i)}$ has the highest net waiting time $T_{net_{wait}}$ value and vice versa)

$Node\_ID$	i^{th}Node Degree (Cnt_{n_i})	Neighbor from $Node_{L_1}$	$Net_{Cnt_{n(i)}}$	$T_{ch_{elec}} = 1 - Log_{10}(Net_{Cnt_{n(i)}})$	$T_{net_{wait}} = T_{ch_{elec}} + T_{wait}$
f	6	2	4	0.397940009	1650.39794
g	5	1	4	0.397940009	1650.39794
h	6	2	4	0.397940009	1650.39794
i	7	2	5	0.301029996	1650.30103
j	5	1	4	0.397940009	1650.39794
k	4	2	2	0.698970004	1650.69897
l	8	2	6	0.22184875	1650.221849
m	6	2	4	0.397940009	1650.39794
w	7	2	5	0.301029996	1650.30103
n	6	2	4	0.397940009	1650.39794
y	7	1	6	0.22184875	1650.221849
p	6	1	5	0.301029996	1650.30103
o	8	1	7	0.15490196	1650.154902

$$* \ \boldsymbol{T_{wait} = T_{ch_{elec}} + \left(T_{est_{tx}} + T_{GI}\right) \times \ Cnt(Node_{L_1})}$$
$$\boldsymbol{= \ T_{ch_{elec}} + (128\mu s + 25\mu s) \times 11}$$

In continuation of the above mentioned scenario, among all the listeners of $Msg(Rply_{DM_{Elec}})$ messages from node (f, g, i, k, l, a, w), $Z(a, k, l, w, m, n)$ and $U(w, m, n, y, p, o, r, q, v)$, nodes $f, l, and\ o$ have the same $Net_{Cntr_{n_i}}$ value but greater than all other nodes. Also their cluster head election waiting time ($T_{ch_{elec}}$) is less than all other nodes of same level i.e. $Node_{L_2}$.Calculation of $T_{ch_{elec}}$ is given in Table 4.7 for selected nodes of $Node_{L_2}$.To break the tie among nodes $f, l, and\ o$ in accessing the channel, CSMA/CA algorithm is tested to be the best choice (Line 16 to Line 23 of Algorithm 5).

Let node l is given the chance to access the network. It's all listeners $(i, j, k, a, t, m. w, n)$ suppress their turn of broadcasting $Msg(Rply_{DM_{Elec}})$ at their allocated time slot since their $Net_{Cntr_{n(i)}}$ is lower (Line 24 to Line 26 of Algorithm 5). Now the node with next highest $Net_{Cnt_{n(i)}}$ value among the remaining $Node_{L_2}$ senses the medium using CSMA algorithm and on finding it free, it transmits $Msg(Rply_{DM_{Elec}})$, say this node is node o. Its listeners (n, y, p, s, v, q, r) have lesser $Net_{Cnt_{n(i)}}$ value. So they suppress their turn and accept the highest degree transmitting node, node o in their footprint as their CH. This process continues until all second layer nodes are engaged into clusters.

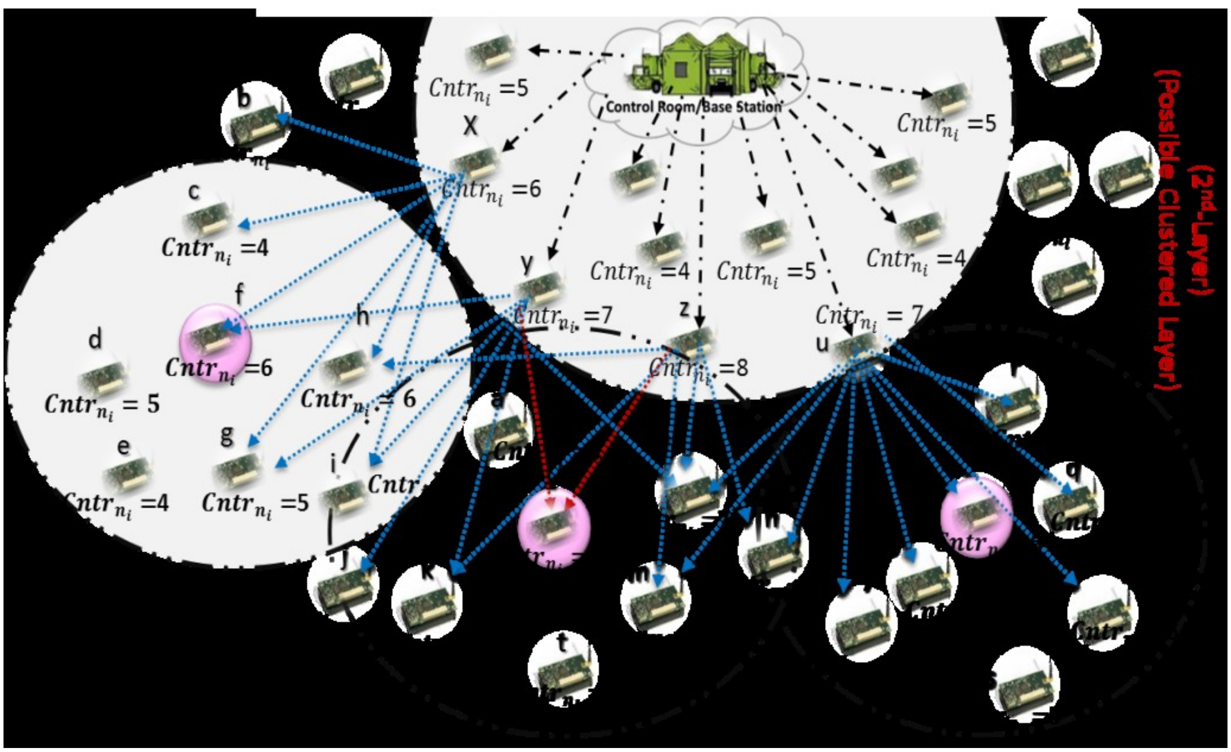


Figure 4.30: Step-1: Completion of the clustering process in 2nd Layer having one cluster highlighted with node '*f*' as cluster head

Figure 4.30 shows the completion of clustering process in 2nd layer having one cluster highlighted with node '*f*' as CH.

ALGORITHM 5. Function of E-MCDA for Clustered Layer

START

If *Node* $\in Node_{L_2}$ **Then**

Set_up array of $Cnt_{n_i} \in Node_{L_1}$

Compare $Cnt_{n_i} \in Node_{L_1}$

Elect $Node_{(dm)}$ *having Max* Cnt_{n_i} *among* $Node_{L_1}$ *in array*

Set timer = $T_{wait_{t_i}}$

If *Cnt [Received(*$Msg_{(CL_{init})}$*)]> 1* **Then**

Consider only 1st

Ignore all later

End if

Each recipient [$Msg_{(CL_{init})}$] calculates $T_{net_{wait}}$

$Net\_Cntr_{n(i)} = Cntr_{n(i)} - (Node(s)_{nbr}\ of\ Node_{L_1})$

$T_{ch_{elec}} = 1 - Log_{10}(Net_{Cntr_{n(i)}})$

$T_{net_{wait}} = T_{ch_{elec}} + T_{wait}$

$Msg(Rply_{DM_{Elec}}) = Node_{(dm_{id})} + Cnt_{n_i}$

$Msg(Rply_{DM_{Elec}})$ *has unique Id*

If $\left(T_{net_{wait}}\right)_i < \left(T_{net_{wait}}\right)_j$ ***Then*** $\forall_j$ *where* $j = 0$ *to* n *and* $j \neq i$

If $Cntr\left(T_{net_{wait}}\right)_i > 1$ ***Then***

Randomly select one based on CSMA/CA algorithm

End if

If $T_{net_{wait}} = true$ ***Then***

Selected $Node_i$ *from* $Node_{L_2}$ *Broadcasts* $Msg(Rply_{DM_{Elec}})$ *to elected* $Node_{(dm)}$

End if

End if

If $Node_{(Rx)} = Node_{L_2}$ ***then***

Suppress their Turn to Broadcast $Msg(Rply_{DM_{Elec}})$

End if

If *Cnt [Received(*$sg\left(Rply_{DM_{Elec}}\right)$ *at* $Node_{(dm)} > 1$ ***then***

$Node_{(dm)}$ *setup array of* Cnt_{n_i}

Compare $Cnt_{n_i} \in Node_{L_2}$

Elect Node among $Node_{L_1}$ *having Max* Cnt_{n_i} *in array*

Designate the elected node as CH

Send $Msg(Reply_{Node_{(dm)}})$ *to elected CH*

End if

End if

End

Figure 4.31: E-MCDA Function for Clustered Layer

If $Node_{(dm)}$ receives more than one $Msg(Rply_{DM_{Elec}})$ messages then $Msg(Reply_{Node_{(dm)}})$ message is sent to only that node which have $Max\ Cnt_{n_i}$ (Line 27 to Line 33 of Algorithm 5). Figure 4.31 shows the pseudo code for the function of E-MCDA for in designing of clustered layer.

4.6.3 '*Required Node Degree*' Based Cluster Member Selection for Near Equal Size Clusters

Proposed work under this section is the improvements in Section 3.2.3. This improved version '*required node degree' based node affiliation algorithm*' helps much in designing near equal size clusters. Figure 4.32 is showing the said typical scenario in the *Extended MCDA* architecture where nodes i, and n are at intersection area (communication range of more than more CHs is overlapping each other) as is highlighted in grey.

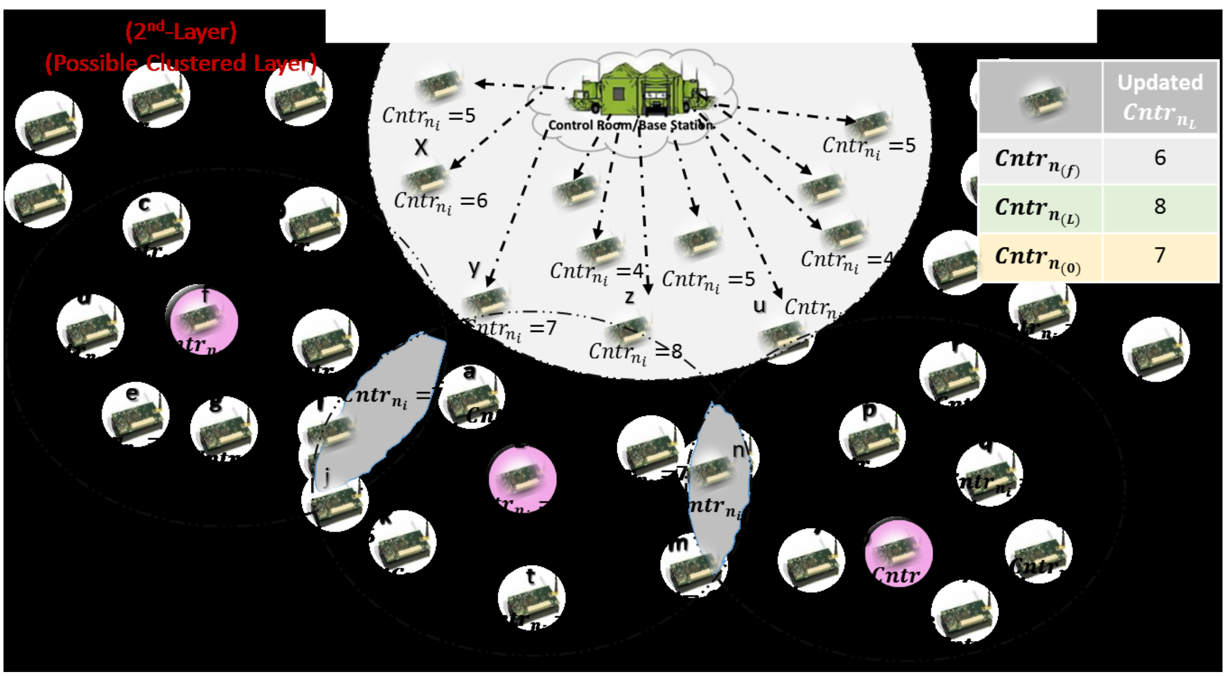


Figure 4.32: Step-1: Nodes at intersection area (highlighted in dark gray)

In a continuation of this, Figure 4.33 depicts the completion of the clustering process at layer 2 with resolving of 'nodes at intersection' issue. To understand how the affiliation of nodes at intersection area to the CHs helps in designing near equal size clusters, we are proposing an algorithm which is explained with an example in subsequent paragraphs.

Let in a scenario having 3 clusters f, l, and o with $Cntr_{n(f)} = 6$, $Cntr_{n(l)} = 8$, and $Cntr_{n(o)} = 7$ and cluster heads $CH(f)$, $CH(l)$, and $CH(o)$. Two nodes i and j are at the intersection of cluster f and cluster l and two other nodes m and n are at the intersection of clusters o and l. Node i sends $Msg_{(join_{acpt})}$message to $CH(f)$ with piggybacking the $Cntr_{n(l)}$ value of its competitor CH i.e. CH_l. The competitor listener CH decrements its $Cntr_{n(l)}$value counter by 1. Since $Cntr_{n(f)} < Cntr_{n(l)}$ so $CH(f)$ sends $Msg_{(join_{acpt_{(ack)i}}})$ message to node i with piggybacking its updated $Cntr_{n(f)}$ value to join it as its cluster member.

Table 4.8: Function of proposed scheme for affiliation of nodes at intersection of communication range of more than one CH

Steps	$Cntr_{n(f)}$	$Cntr_{n(l)}$	$Cntr_{n(o)}$	Nodes at intersection of	
				f, and l	l, and o
1	6	8	7	i, j	m, n
2	6	7	7	j	m, n
3	6	7	6	j	n
4	6	6	6	0	n
5	6	5	6	0	0

Step 2 in Table 4.8 shows the update status of clusters at this stage. As $CH(l)$ has lost its one potential member node, so it sends its latest value of $Cntr_{n(l)}$to update its neighbors. Now the turn is of node m that is placed at the intersection of communication range of cluster l and cluster o. Since $Cntr_{n(l)} = Cntr_{n(o)}$, so tie rises in selection between these two. On random choice let $CH(l)$ is selected. Then node m sends ($Msg_{(join_{acpt})}$) message to $CH(l)$ in the same fashion as mentioned in case of Node i and receives $Msg_{(join_{acpt_{(ack)}i})}$ message by $CH(l)$ with piggybacking its updated $Cntr_{n(l)}$ value. Here $CH(o)$ decrements its $Cntr_{n(o)}$value counter by 1 due to loss of one of its potential member node and sends its latest $Cntr_{n(o)}$value to update its neighbors. Step 3 in Table 4.8 shows the update status of clusters at this stage. Similar process continues until remaining two nodes j and n in the given scenario are also affiliated to the clusters having lowest current $Cntr_{n(i)}$value among their inviter. Step 5 in Table 4.8 shows the final status of clusters$f$, l, and o after breaking the overlap conflict. Now it seems to be near equal sized clusters.

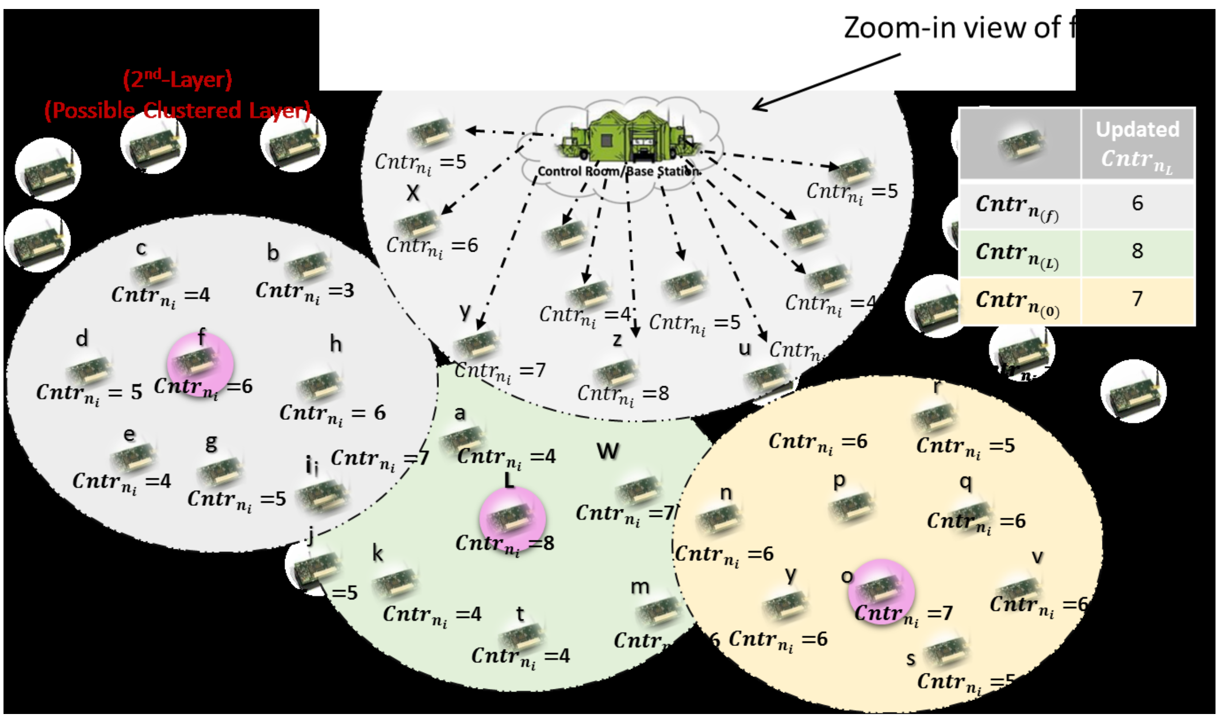


Figure 4.33: Step 2: Completion of clustering process at layer 2 with resolving of 'nodes at intersection' issue

If we do a theoretical comparison of proposed solution with the generic method of nodes' affiliation that are placed at the intersection of communication range of more than one CHs then we come up with the following Table 4.9. In generic method, node is affiliated to the CH with the lowest degree for the sake of equalizing the cluster size. It shows that the sample variance of the generic method is far greater than that of proposed solution.

Same is also drawn in Figure 4.34. Derived from this result, performance efficiency (ρ) of proposed method over simple method is 86% using following formula.

$$\rho = 1 - \left(\frac{Sample\ Variance\ of\ Proposed\ Scheme}{Sample\ Variance\ of\ Simple\ Schme}\right)$$

This improved performance results in near equal sized clusters that help in a balanced load over cluster heads that results in less frequent cluster head rotation and hence better network performance and improved network life time.

Table 4.9: Comparison of generic and proposed technique for decision parameter for affiliation of nodes at intersection of communication range of more than one CHs

	CH Affiliation Decision Parameter	
	Generic	Improved/Proposed
$Cntr_{n(f)}$	6	6
$Cntr_{n(l)}$	4	5
$Cntr_{n(o)}$	7	6
Sample Variance	2.33	0.33
Performance efficiency of the proposed method over generic method		86%

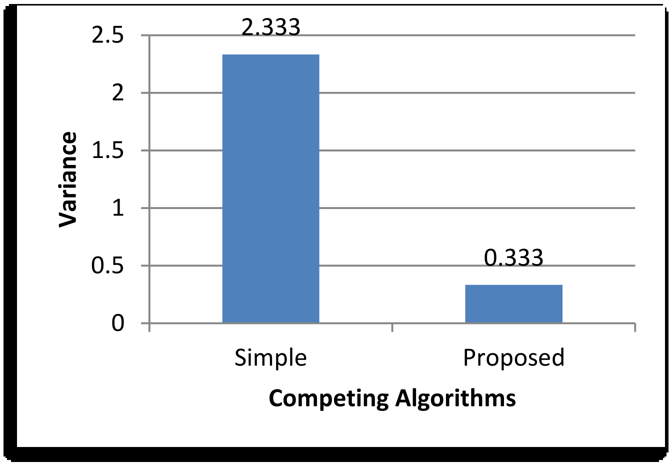


Figure 4.34: Sample Variance of Competing Algorithms on equality of cluster size

4.7 Comparative Analysis of E-MCDA with State-of-the-art Algorithms

In this Section, a comprehensive discussion is made on the comparative analysis of E-MCDA with the state-of-the-art related algorithms. Table 4.10 shows the simulation parameters taken during our experimentations.

Table 4.10: Simulation Parameters

Parameter	Description
Routing Protocols	EADUC, MCDA, E-MCDA (Proposed)
Simulation Area	500m x 500m and 1000m x 1000m
Simulator	NS 2.31
Data Rate	4 Packets/Sec
TCP/IP Layer	Network Layer
Node to Node Distance	Random
Node Type	Homogenous
No. of Nodes	500
Propagation Model	Two ray ground
Initial Energy of Node	3 Joule

Transmission of packets in the network, layer wise and per node, energy consumption in and other than packet transmission, cumulative, total and average energy consumption of network, per node, and layer wise, number of clusters, number of member nodes per cluster and number of un-clustered nodes are taken into account as performance evaluation parameters for the comparison of aforesaid algorithms. Demonstration for the same is depicted in different figures starting from Figure 4.35 to Figure 4.59. Since the experimentation is performed with same number of deployed nodes i.e. 500 in two different areas i.e. 500m x 500m and 1000m x 1000m, so the representation of results is given accordingly.

4.7.1 Deployment area of 500m x 500m

In this subsection, the results taken from the simulation scenario whose parameters are same as are given in Table 4.10 with deployment area of 500m x 500m.

Although clustered network is the proven architecture in prolonging the network life time yet the prior step of this operational clustered network is formation of clusters that cost something in the form of higher energy consumption compared to setting up cost of flat network. Information collection, competition among candidate nodes to be final cluster heads, and announcement of being CH are the key steps to perform to make the network operational. Transceiver's and processor's activities (transmission, reception, calculation, waking and sleeping modes etc.) mainly decide the cluster formation cost. The cluster formation idea in EADUC sensibly conserves the energy in its distributed cluster formation. The introduction of waiting time $'t'$ that really decreases plenty of broadcasts and related calculations plays vital role in it. But in contrast to this, the strategy adapted to generate unequal clusters through the calculation of competition radius RCcauses the network messy with too much broadcasting since the values of $d_{max}$and $d_{min}$are the parameters of this calculation. Each network node needs to communicate its calculated value$d(S_i, DS)$i.e. distance from node $S_i$to the Base station (DS). BS extracts the d_{max}(maximum distance to BS), and d_{min}(minimum distance to the BS) and communicated back to the network nodes for their use in calculation of RC. This style encompasses all the drawbacks encapsulated in centralized cluster designing approach. Bigger the network size (network of 500 nodes in our case), more the involvement of transient nodes to communicate the info of distantly placed nodes to the BS. While in case of MCDA, this messy type of engagement of transceiver and processor for information collection and dissemination until BS is no more due to the introduction of $P(Seq_{no})$, limited and optimized competing nodes(dm_{id}) and selected listeners' response.

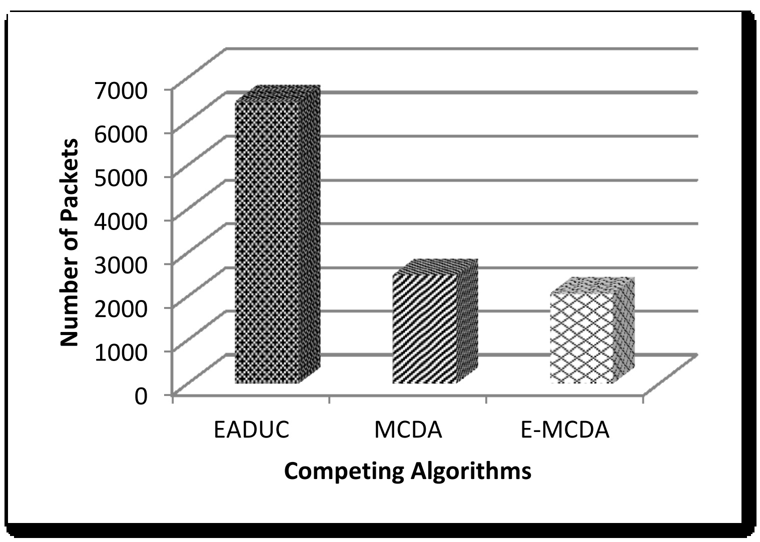


Figure 4.35: Total No. of Packets Transmitted During Cluster Designing

This idea is more improved in E-MCDA where the idea of MCDA is simplified by $T_{net_{wait}}$that further decreases broadcasts and substantially reduces the number of cluster head candidate nodes. Hence, number of packs transmission (unicast, broadcast etc.) is highest in EADUC compared to MCDA and it has more than E-MCDA. This comparison is depicted in Figure 4.35.

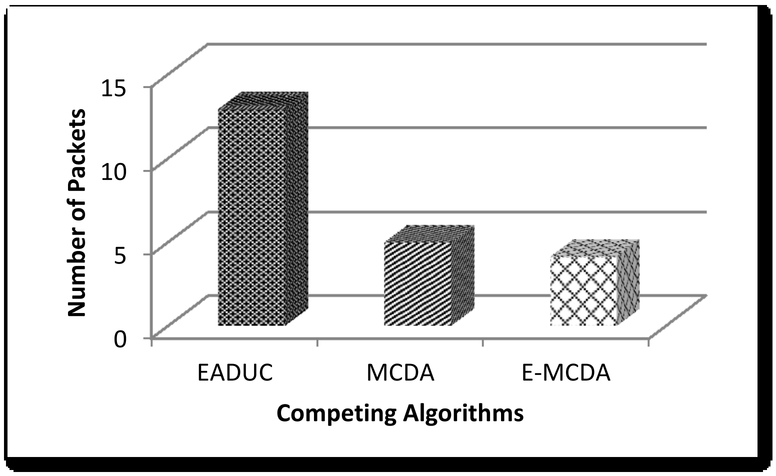


Figure 4.36: Average Number of Packets Broadcast Per Node during Cluster Formation

. More-over, Figure 4.36 also gives backing to it where per node average number of packets transmission during cluster formation process is shown.

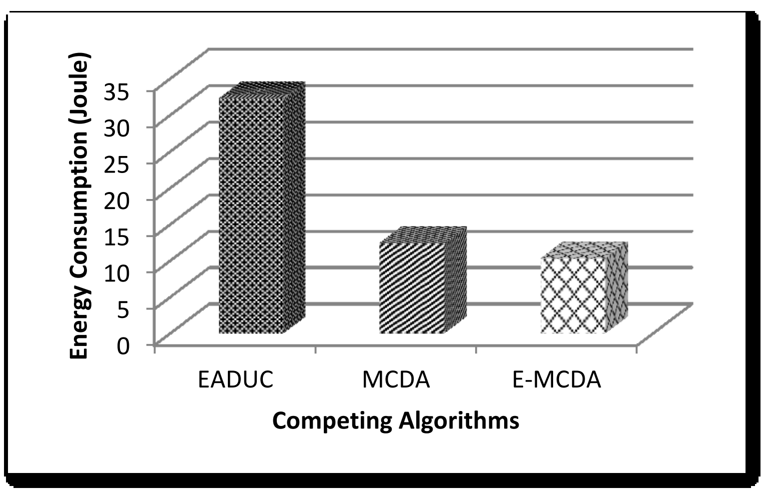


Figure 4.37: Energy Consumption in Packet Transmission in Cluster Designing Process

Same differentiation in the form of energy consumption comparison is also reflected from Figure 4.37. Next to the crucial factors of BS in energy consumption are reception and calculation, etc. Considering these performance evaluation parameters, the working presentation of MCDA and E-MCDA are almost same with little difference while EADUC shows higher energy consumption than others due to the calculation of E_a, t, and RC which further have such calculations.

Apart from it, more packets transmission/broadcast means more nodes are involved in packet reception as is depicted from Figure 4.38 and Figure 4.39. EADUC has higher number of packets transmission than other two, so more packets reception in resultant also. Hence Figure 4.38 depicts more energy consumption of EADUC during cluster formation other than BS transmission process.

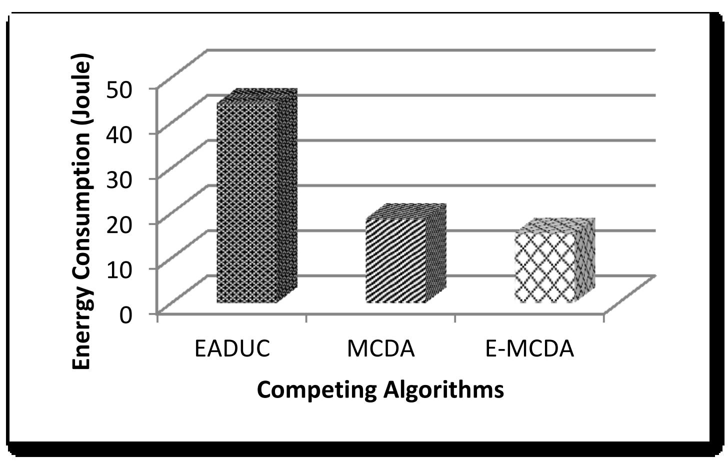


Figure 4.38: Total Energy Consumption during Cluster Designing Process

Another notable point is while comparing Figure 4.38 and Figure 4.37 is that difference in energy consumption of EADUC is about 12 $Joule$ $(44 - 32)$while in case of MCDA it is 6 $Joule$ $(18 - 12)$ and in E-MCDA difference is 5 $Joule$ $(15 - 10)$. So, EADUC has almost double in difference value compared to MCDA and E-MCDA showing the role of other factor(s) than transmission i.e. reception and calculation.

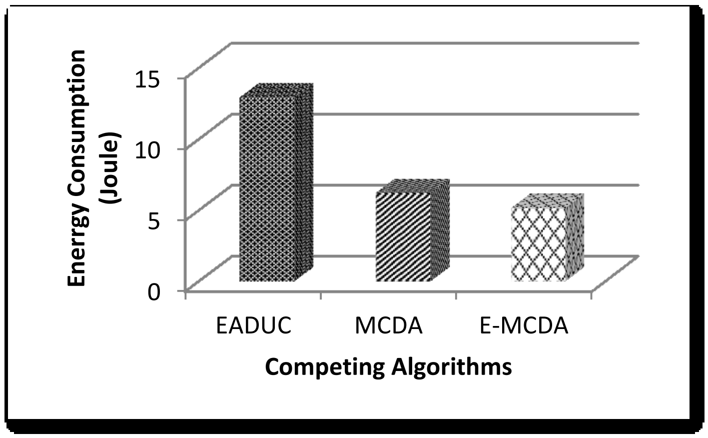


Figure 4.39: Energy Consumption other than Packets Transmission during Cluster Designing

Figure 4.38 reveals this effect with the proof of the fact that packet transmission matters much in network life time compared to receiving and calculation factors. In support of this, there is another empirical fact that energy consumption during transmission of a packet is equal to 1000 calculations and almost the same ratio with packet reception.

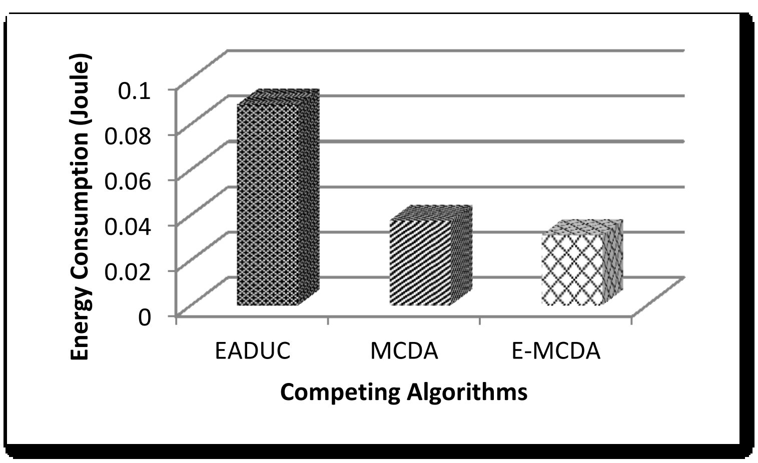


Figure 4.40: Per Node Average Energy Consumption during Cluster Formation

Consequently, a clear reflection from Figure 4.39 is that the main outperformance edge of E-MCDA over MCDA and EADUC is controlled transmission due to the introduction of $T_{net_{main}}$ and very selective CH competition candidates. Same is also intuited from Figure 4.40 with the representation of per node average energy consumption. Consumed energy of network nodes can also be represented in another way in order to give another backing to the aforementioned claim regarding effect of broadcasting over energy consumption.

In Figure 4.41, energy consumption is calculated in cumulative. As in E-MCDA and MCDA nodes grouping is made into layers i.e. flat layer N_{L_1}, clustering layer 1 N_{L_2}, clustering layer 2 N_{L_3} etc. In accordance with this scenario of layering of nodes, cumulative energy consumption in EADUC is calculated in the same way. As estimated counting of nodes in generated five layers (groups) are 95, 85, 120, 130 and 70 (layer 5 to layer 1 respectively) cumulative to 95, 180, 300, 430, and 500 nodes with cumulative energies as shown in Figure 4.41.

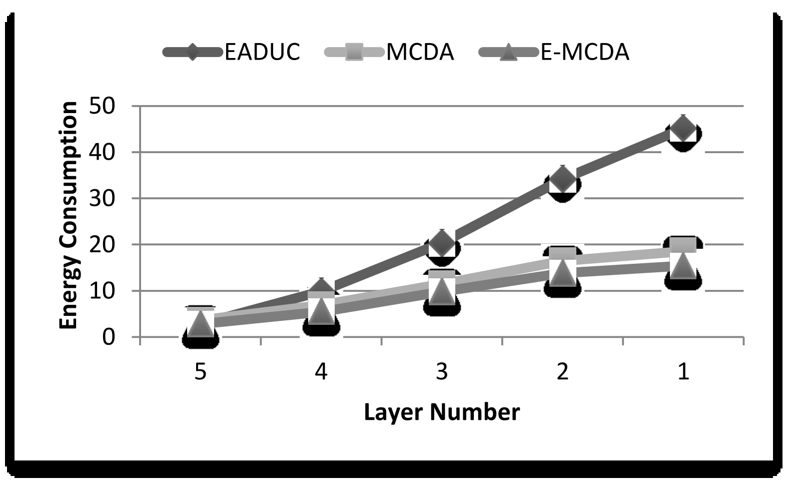


Figure 4.41: Layer Wise Cumulative Energy Consumption

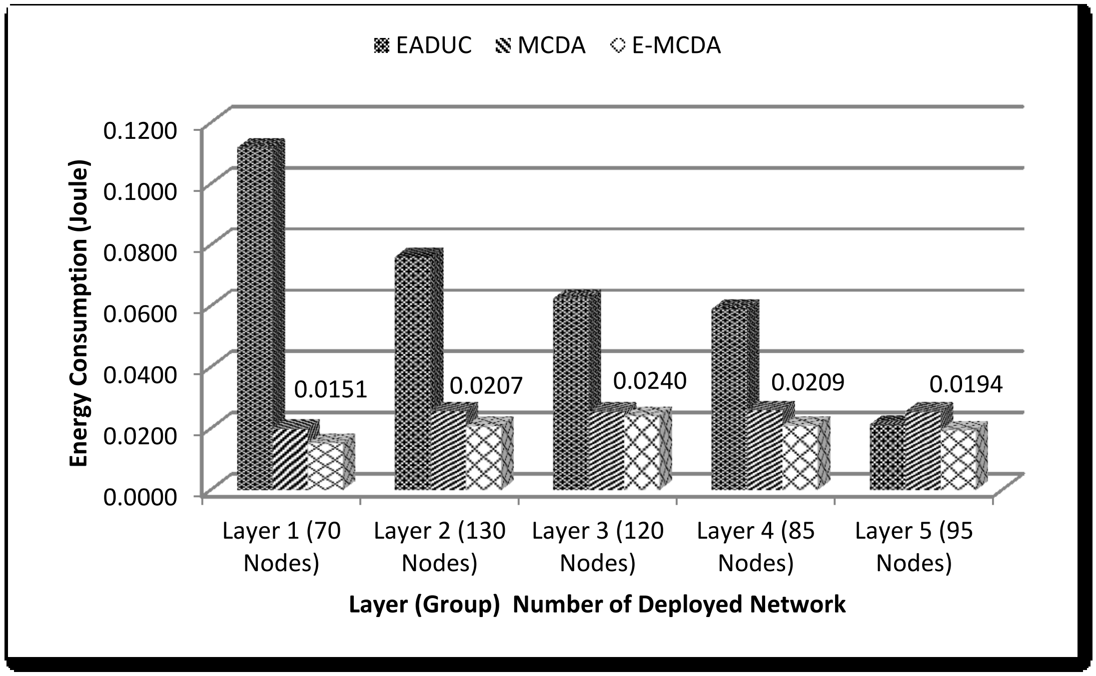


Figure 4.42: Layer Wise Average Energy Consumption during Cluster Formation

It is reflected from the line graph that energy consumption for EADUC is inversely proportional to the proximity to BS with sharp a hike in trend the line. While in case of other two competing mechanisms; MCDA and E-MCDA energy consumption line is gradually increasing. Cumulative energy consumption line of MCDA is comparatively higher than the E-MCDA because of relatively more broadcast (more involvement of cluster head candidate nodes). Accumulation of energy consumption values are performed from last layer (layer 5 in our case) to first layer since it better represents the sharp hike in energy consumption line and load on the nodes closer to BS compared to its opposite side representation. Another aspect of load and energy consumption relationship is shown in Figure 4.42.

In E-MCDA, energy consumption is almost consistent in all the layers except the first layer (group) because E-MCDA does not form clusters in the first layer. This flat layer (un-clustered layer) does not suffer from energy loss due to clustering designing process. Same is the case with E-MCDA. More-over, in case of EADUC in the last group (layer), average energy consumption is almost same as that of MCDA and E-MCDA. It is also intuited from the result that energy consumption in the process of cluster formation matters to be considered that also validate and support our research problem and research contribution.

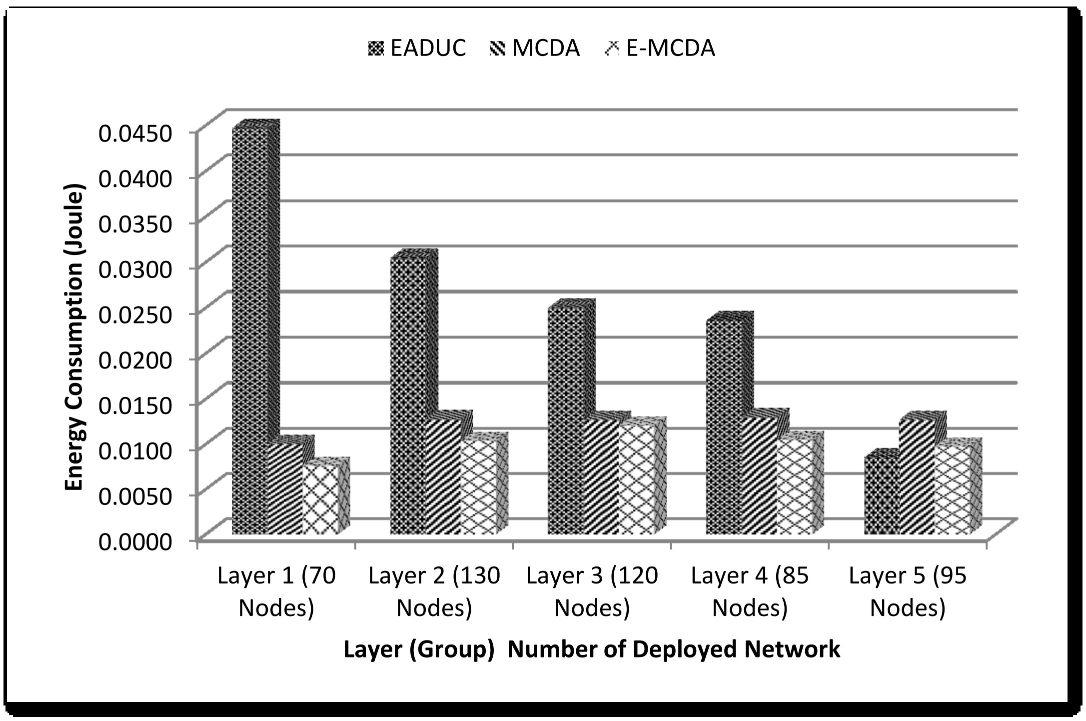


Figure 4.43: Layer Wise Average Packets Transmission during Cluster Formation

Same effect of work load and node involvement over energy consumption in resultant is shown in Figure 4.43 where packets transmission is more on the nodes closer to BS in contrast to the farther nodes. Considering the residual energy factor in cluster head selection and cluster formation is not always a foresighted decision. In start of network operation almost all the network nodes have same energy level but with the passage of time energy difference (delta energy, ΔE) increases and ultimately at a stage this ΔE

becomes very big. This situation is very inappropriate and unsuitable for considering only energy as CH decision metric.

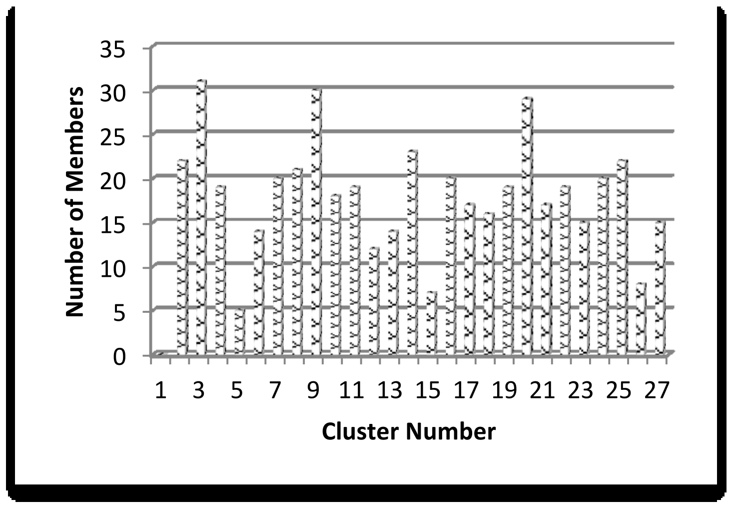


Figure 4.44: Number of Cluster Members in EADUC

The big drawback of this choice comes in the form of such clusters having less and sparsely placed nodes even clusters with only one member node. On comparing the effect of E-MCDA, MCDA and EADUC over the cluster members in Figure 4.44, Figure 4.45, and Figure 4.46 respectively we come up with the proof of the aforementioned claim. The most fluctuating trend line is of EADUC. It takes the reason that the authors did not consider the node density in generating the clusters, and residual energy is node is the only factor considered for CH selection/ cluster formation.

More-over, in EADUC cluster size is a direct function to the distance to BS. Combining these two working aspects of EADUC, we come up with the result in the possibility of two extreme cases in the designed clusters; i) Small clusters with high nodal density ii) Large clusters with lower nodal density. With this uncontrolled situation, the strategy of EADUC's authors for introducing energy awareness in distributed cluster designing becomes less effective. This uneven distribution scenario is not very uncommon in random and non-uniform deployment of nodes.

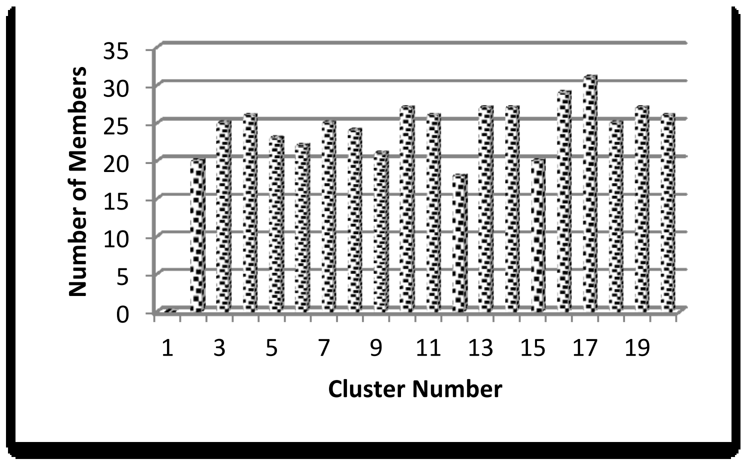


Figure 4.45: Number of Cluster Members in MCDA

The most consistent size (density) of clusters are of E-MCDA because the first priority given to the CH decision metric is of nodal density that limits the network to suffer from same issue as in case of EADUC due to aforementioned reasons. Comparative graph of three mechanisms on number of designed clusters for 500 deployed nodes is demonstrated in Figure 4.47. It is also clear from the graphs that the designed clusters in MCDA and E-MCDA are almost same but EADUC make more clusters due to aforementioned reasons.

Another factor that affects the cluster density is of decision strategy relating to nodes' placed at the intersecting area of adjacent clusters. Both the EADUC and MCDA follow the $'proximity\ to\ CH'$ strategy to take their joining decision. This may result in big imbalance in adjacent clusters density. This point is well explained in Section$'Cluster\ Member\ Selection'$ of this article. Figure 4.44, Figure 4.45, Figure 4.46 strongly supports this statement with worst to best effect of decision strategies of above issue.

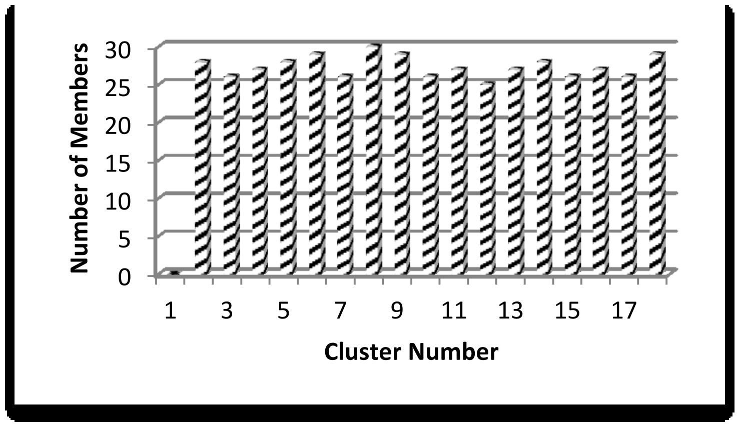


Figure 4.46: Number of Cluster Members in E-MCDA

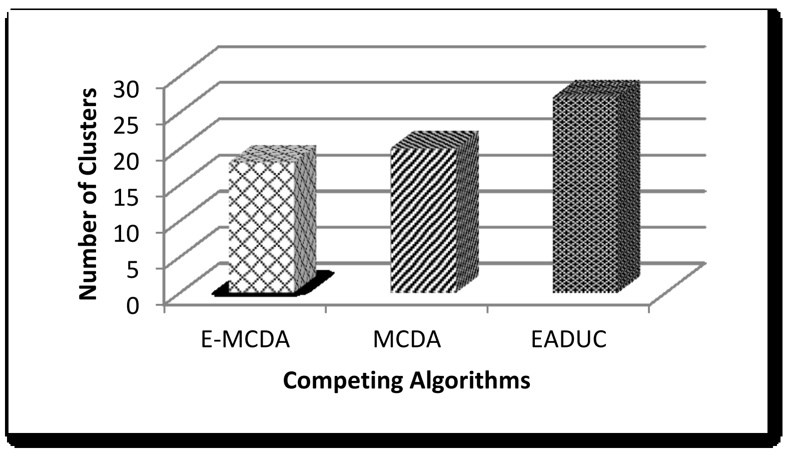


Figure 4.47: Number of Clusters

Reflection of near equal size clusters of E-MCDA is better reflected from Figure 4.48 which has lower standard deviation value compared to MCDA while for EADUC it is highest. Here we have calculated the standard deviation using "n" method with the formula $\sqrt{\frac{\sum(x-\bar{x})^2}{n}}$. Clusters nearer- to the BS have very small density (even they have the cluster members less than 5) compared to the clusters designed farther from BS that have cluster members even greater than 30.

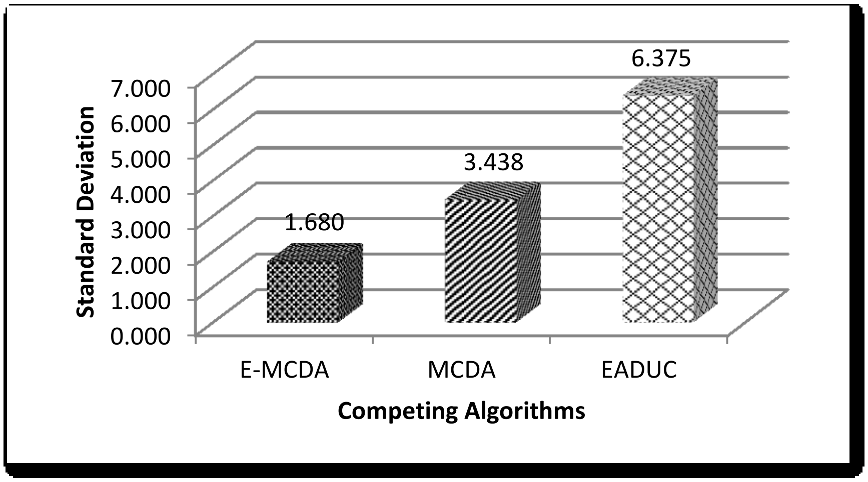


Figure 4.48: Standard Deviation of Number of Members per Cluster

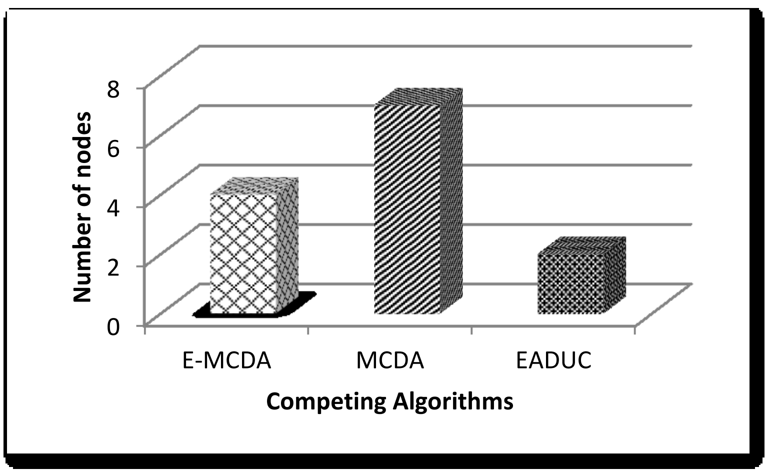


Figure 4.49: Number of Un-clustered Nodes

Strategy adopted in EADUC for unequal clusters also lead to un-usual number of clusters since, if a deployed node does not receive any join request from the cluster head, it announces its status as CH. This leads to more clusters. Number of clusters in the network further opens a new talk for its effect on the network life time. In short, more clusters increase load on hotspot area and very fewer clusters increase the load on cluster head. Hence, there must be a moderate way on the number of clusters in the network.

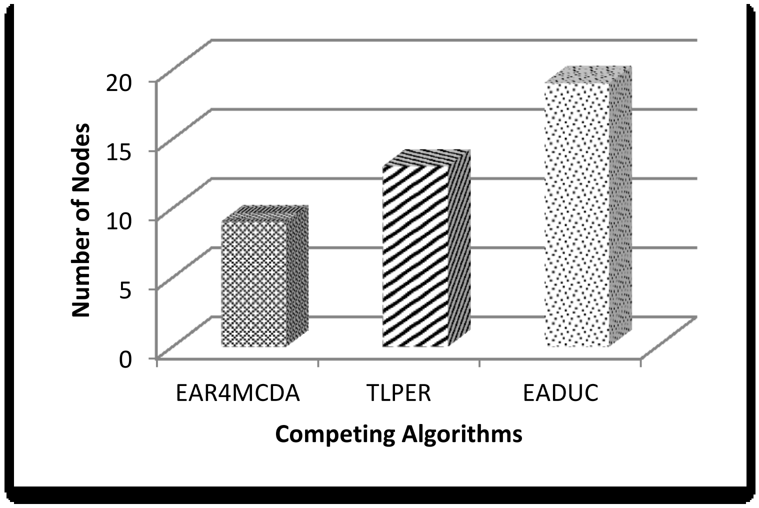


Figure 4.50: Number of un-clustered nodes after 1000 sec. of running simulation

Since in EADUC, even a single node advertises itself for being cluster head, if it does not receive the join invitation message from neighboring clusters. So, if we consider these nodes i.e. cluster heads with no cluster members, then the highest un-clustered nodes are of EADUC as shown in Figure 4.50. EAR4MCDA gives the best results with least number of un-clustered nodes.

Same greedy strategy of the cluster designing in EADUC also results in very less un-clustered nodes compared to other two as shown in Figure 4.49. Last but not least, cluster formation time as in Figure 4.51 reflects the efficiency of algorithms in completion of setup phase and making the network ready for operation. The importance of this time various from application to application. Cluster formation time in MCDA is slightly higher as compared to EADUC. In MCDA, there is layer wise design flow and it needs more time compared to traditional distributed network design. But in case of EADUC, too much information collection from neighboring nodes for selection of cluster head add more time in cluster formation process.

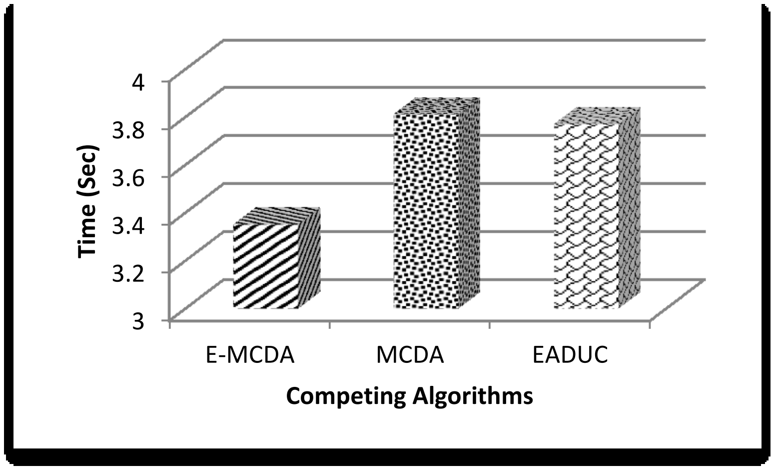


Figure 4.51: Cluster Formation Time

This makes its cluster formation time closer to MCDA. But in case of E-MCDA, there is less no. of involvement of nodes in cluster head selection. This not only save the network energy but also has its role in decreasing the cluster formation time.

4.7.2 Deployment Area of 1000m x 1000m

In this subsection, the presented brief discussion covers two aspects. First is the results taken from the simulation scenario whose parameters are same as are given in Table 4.10 with deployment area of 1000m x 1000m. Second is the performance efficiency of proposed solution over other two competitive solutions at the deployment areas of 500m x 500m and 1000m x 1000m. The depiction for the same is given from Figure 4.52 to Figure 4.59. Since the reasoning of better comparative performance is the same as is comprehensively elaborated in previous subsection (4.7.1), so here we are just highlighting the impact of increased deployment area over the extracted results.

On increasing the deployment area by keeping the number of nodes and all other factors constant, on the average, the node density per unit area decreases. This new scenario may have following effect on various aspects of network and communication thereon as compared to the previously given scenario. These effects may be more number of clusters, less number of cluster members, more number of forwarding nodes and hence more end to end delay, less number of recipient nodes of same typical broadcast and hence less messages in reply, more time in completion of network set up phase, less memory and processing load due to less number of neighbor nodes and less nodes at the intersection point of neighboring nodes' (CHs) communication range.

Impact of controlled broadcasting, selective candidate nodes for being CHs, and hybrid approach is also clearly reflected from the comparative results given in Figure 4.52. Total energy consumption in E-MCDA is still far better compared to MCDA and EADUC. On comparing Figure 4.52 with Figure 4.38, the overall consumption is decreased in underlying sparse network. Among the aforementioned effects, the major one is less number of recipient nodes of some typical broadcast and hence less message in reply.

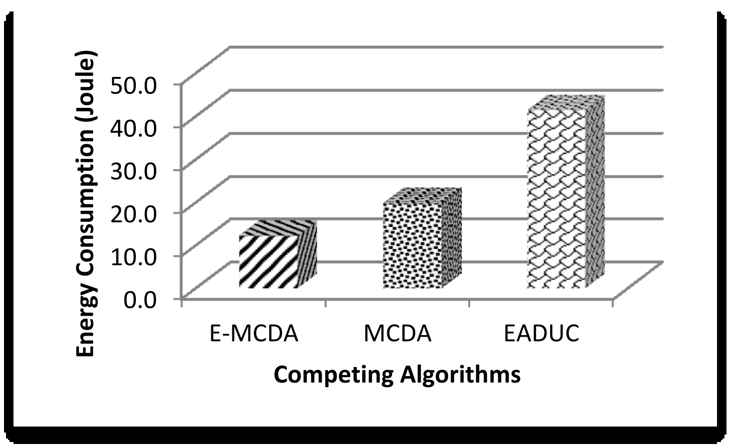


Figure 4.52: Total Energy Consumption in Cluster Designing in 1000m x 1000m Area

Hence, in Figure 4.53, performance efficiency of E-MCDA over MCDA is a bit higher in current deployment area compared to previous scenario. In MCDA, number of designed clusters is 70% more in 1000m x 1000m area compared to node deployment in 500m x

500m area while in E-MCDA, this value is 56% as is intuited from comparing Figure 4.54 and Figure 4.47. This aspect is stronger in EADUC compared to other two. Since in EADUC, clusters size is unequal. Farther the cluster position from the BS, bigger is its size. Therefore, this value of higher number of clusters in 1000m x 1000m area is about 45% compared to other scenario. But on the other end, the strategy adapted by EADUC in designing these unequal clusters is very expensive due to the information collection for constituent parameter.

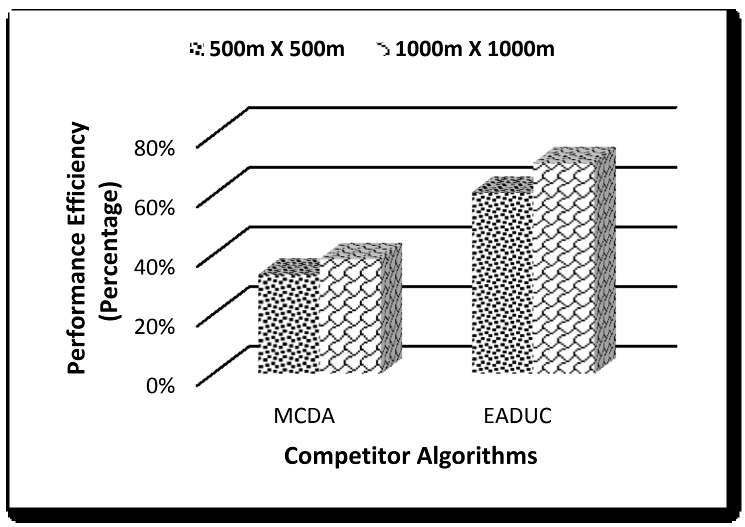


Figure 4.53: Performance Efficiency of E-MCDA in Total Energy Consumption during Cluster Designing over Competitor Algorithms

This increases the total energy consumption bar in Figure 4.52 and in Figure 4.53 as well. This style also increases the exchange of messages. Hence, number of broadcast in EADUC is 40% higher in under discussion deployment area compared to densely node deployment in 500m x 500m while in MCDA and E-MCDA, this value is 11% and 10% respectively. Figure 4.55 and Figure 4.56 also extend this comparison in representing number of packets broadcast during cluster designing and the performance efficiency of E-MCDA in number of packets broadcast during cluster designing process over competing algorithms.

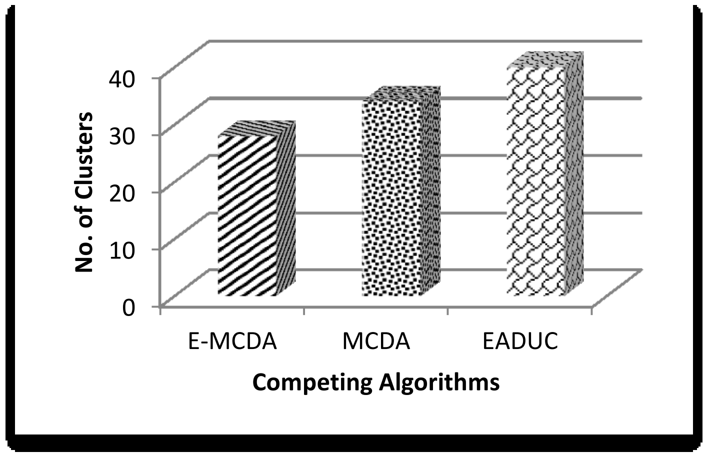


Figure 4.54: No. of Clusters Designed in 1000m x 1000m Area

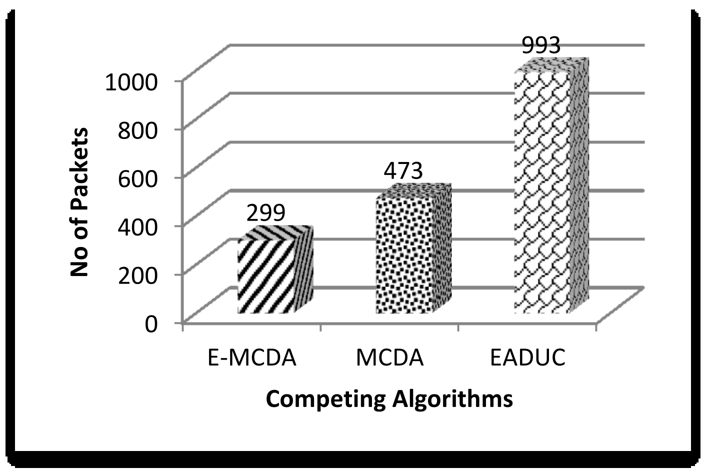


Figure 4.55: Number of Packets Broadcast during Cluster Designing Process in 1000m x 1000m Area

In continuation to it, its impact on energy consumption aspect is depicted in Figure 4.57. Extending to it, the comparison of performance efficiency of E-MCDA in energy consumption during broadcast transmission process in deployment areas; 500m x 500m and 1000m x 1000m and that of MCDA and EADUC is depicted in Figure 4.58.

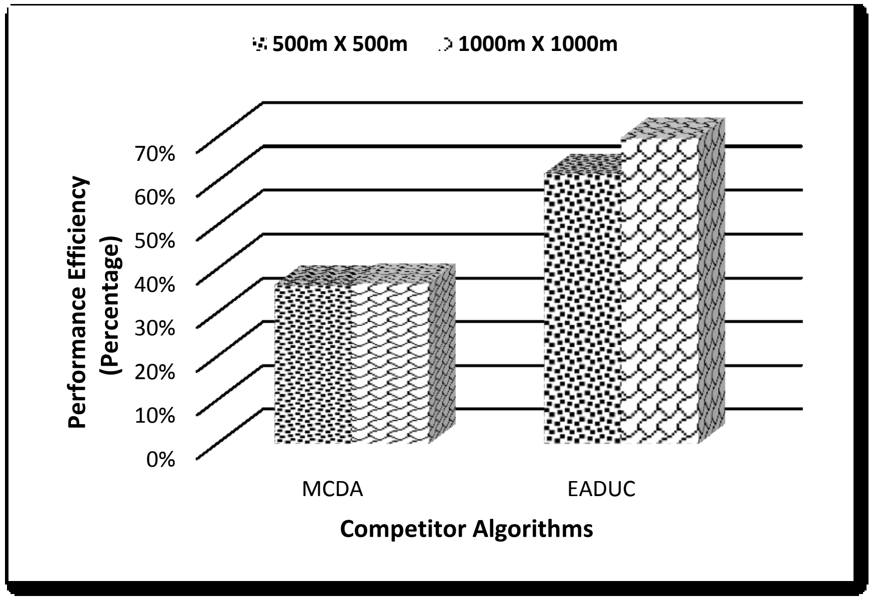


Figure 4.56: Performance Efficiency of E-MCDA in Number of Packets Broadcast During Cluster Designing Process over Competitor Algorithms

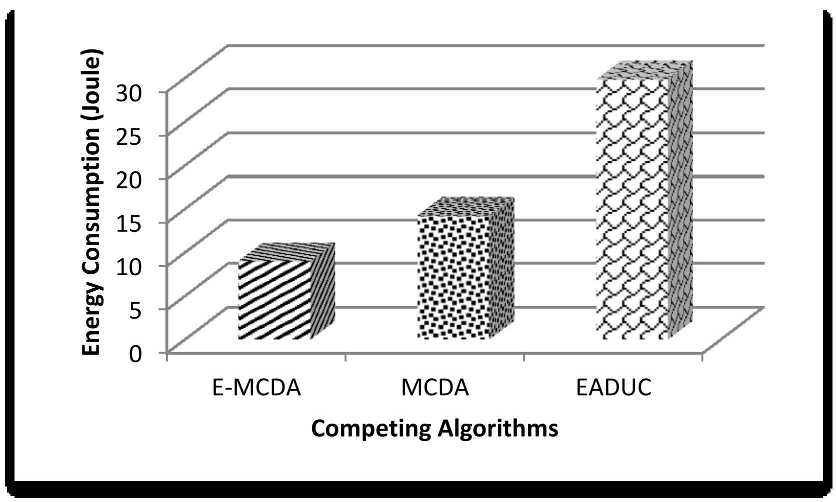


Figure 4.57: Energy Consumption in Broadcast Transmission in 1000m x 1000m Area

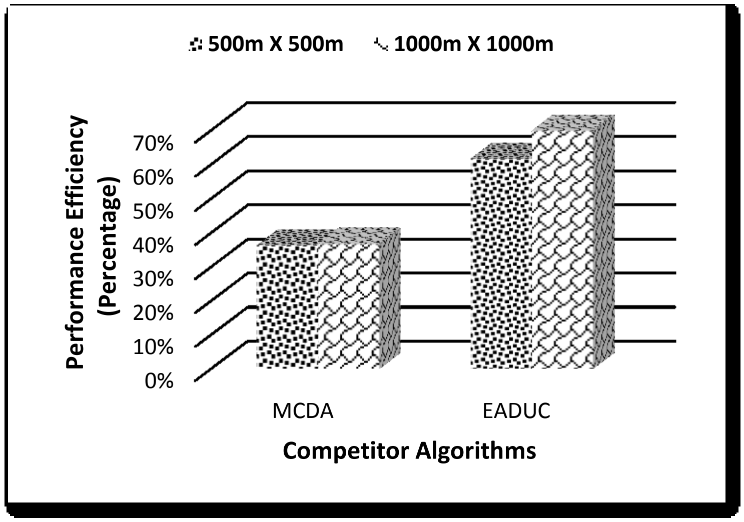


Figure 4.58: Performance Efficiency of E-MCDA in Energy Consumption during Broadcast Transmission Process over Competitor Algorithms

Another important effect of increasing the deployment area by keeping the other aspects same as that are of comparatively smaller area is the decrease in node density in cluster i.e. lesser CMs. This has two fold effects. One is more number of clusters in the network and the other is less nodes at the intersection point of neighboring cluster heads communication range. Sufficient detail has already been dedicated to first point in previous paragraphs. So far as decision for affiliation of nodes at intersection points is concerned. It shapes the cluster size and ultimately has its impact on CH rotation or cluster re-designing strategy. Refer to Figure 4.59, a big value of standard deviation in case of EADUC shows higher difference in clusters size compared to that of in MCDA and E-MCDA. This burdens the CHs with more memory and processing load in larger clusters and special intra-cluster routing strategy as well. This further opens the numerous issues to handle.

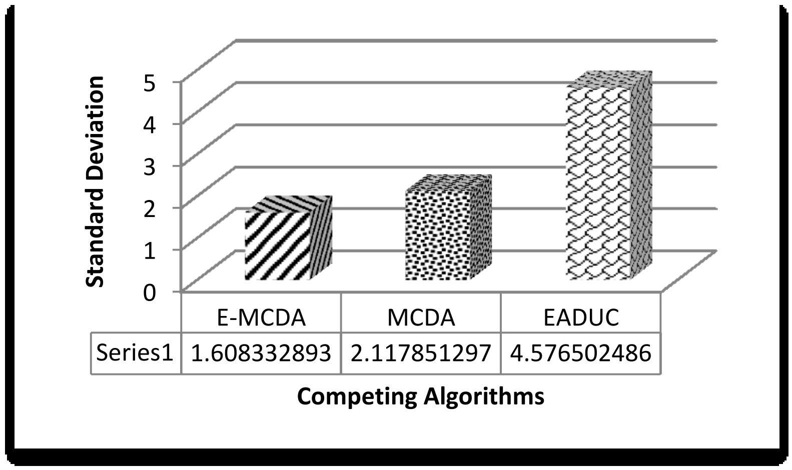


Figure 4.59: Standard Deviation of Number of Members per Cluster in 1000m x 1000m

Chapter 5

5 Energy Aware Routing over MCDA

5.1 Introduction

Wireless sensor network nodes are highly dependent on batteries in their tracking, surveillance, and monitoring, sensing and computational applications. Due to their unattended and far distant deployment, replenishment of batteries is almost impossible. So, any designed application and algorithm for this energy constraint technology of wireless sensor network should be energy aware. Communicating the sensed data from the source node to the base station that is known as routing is the core functionality in this deployed network. Among the communication models, direct hop fits better for small scale networks where the nodes communicate directly to the base station. The approachable network size is a function of maximum communication range of node. For large scale networks, multi-hop communication model provides scalability through the transit nodes' assistance to destine the data to far distantly placed Base Station (BS). Simulation based comparative analysis of this direct hop and multi-hop communication to the base station is given in detail in [79].

For minimum utilization of battery, all the steps from node deployment to network architecture (Clustered Network) and from environment sensing to communicating the sensed data to the base station (routing) should carefully be designed. Lessening the broadcasting, and decreasing computation and packet overhead add better role in the energy conservation and ultimately helps in increasing the throughput and network life time. In this research work, we have targeted this issue of ameliorating the network throughput from the aspect of energy conservation for routing functionality in clustered network.

Figure 5.1: Various Roles of Node during its Life Time in Clustered Network Architecture

In this type of architecture, nodes are grouped together in a cluster with designating one node as their head called CH and other nodes in the clusters as CM. In the clustered network, the process of designating a node as the cluster head i.e. CH election is usually the initial phase. While establishing the route for communicating the data from the source to destination is usually its last phase [79]. However, this sequence is not always the case. Hence, in clustered network architecture, nodes are designated different roles. Figure 5.1

shows the possible roles of a node during its life time depending upon the underlying clustering algorithm. The role of the node that are underlined in the figure are the part of every clustering algorithm. For better understanding of the role, short description is also given with each one. Clustered network is considered to be the most energy efficient architecture due to its ease in route discovery, fault tolerance, data aggregation and shortest possible end-to-end delay nature [155].

Literature is rich in cluster based routing protocols that mostly encompasses, i) cluster designing, ii) route establishment and iii) cluster head rotation processes. Cluster designing consists of cluster head selection, cluster member affiliation to cluster head and time slot assignment for communicating the sensed data to CH. All the proposed algorithms for the same either accomplish these processes with central control of BS [86] or locally controlled distributed style [137]. Both the techniques have their pros and cons. Cluster designing part from the aforementioned three steps has already been discussed in detail in previous chapters since this work is the continuation of our previous work [79] where we proposed a novel technique of multilayer cluster designing for network life time improvement of homogenous wireless sensor networks. 2^{nd} (route establishment) and 3^{rd} (cluster head rotation) steps are covered in this chapter. Proposed schemes for both the steps work on the network architecture presented in [79].

In exploiting this architecture, we offer here suitable algorithms for designing routing (inter-cluster and intra-cluster) and cluster head rotation. All nodes at first tier (first layer) act as forwarding node for the second tier CHs. Cluster Heads of each subsequent layer communicate to CHs of preceding the layer either directly or through intermediate node that once acted as decision maker node in the election of CH during cluster designing process. Threshold levels are introduced at the node energy to initiate the process of CH designation rotation. Role is transferred to the most energy carrying nodes in two steps. These strategies in collaboration with the MCDA's architecture work well to give reliability (safe and step wise role transfer), fault tolerance (higher density node selection for CH and for decision maker node and so for the forwarding node), better throughput and improved network life time (balanced network utilization, less inter node communication, removing hot spot area in the neighbor of BS etc.).

5.2 Proposed Solution

Routing algorithm for clustered network is designed either by exploiting the cluster designing process or a separate standalone process is initiated for it. Here in this section, an energy aware routing strategy is presented for MCDA by exploiting its designing process. No extra much broadcasting for forwarding node selection or route establishment is needed since it is pre-set and pre-planned during the cluster designing process. This section is divided into 3 sub sections; i) Analysis of MCDA for designing energy aware routing algorithm and to highlight the spectacular features for improved performance of the same ii) Introducing the cluster head rotation process iii) Complete routing process.

5.2.1 Analysis of MCDA for EARS

Working of MCDA in a summarized form has already been presented in section 2. In a continuation of it, here we present the analysis for highlighting the parameters that can be used for designing energy aware routing algorithm. Layer 1 nodes broadcast their node density value. The listener nodes of this broadcast among second layer nodes set a forwarding node table having node IDs in the precedence level of their node density. Table 5.1 shows the sample format of the same for a typical node, say node $'w'$.

Table 5.1: Forwarding Node Table at node 'w'

Decision Maker Candidate Node ID from Layer 1 Nodes	Node Density
Y	7
U	7
Z	8

The underlying node first selects the node from $'Forwarding\ Node\ Table'$ with highest nodal density. Since the network is homogenous and energy consumed in cluster designing is almost equal in all nodes, so energy delta ΔE is very less among the nodes. Hence, all the three nodes of layer 1 (as shown in Table 5.1) have almost same energy levels. In view of it, the highest degree node is selected first as FN from this Forwarding Node Set (FNS). Higher node degree means more neighbors and so the big FNS related to it to share the load of each other and also more nodes to tolerate any expected fault of node. More-over, the rotation of designation of FN is also easy. For the process of rotation of FN, we are introducing Two-Level threshold strategy. First level; Load Balancing Threshold triggers the load balancing process and the second level; Role Transfer Threshold is for transferring the role of being FN to some other suitable node. We are using almost same technique in the rotation of CHs in subsequent tiers of our multilayer clustered network architecture. The CHs of first clustered layer (i.e. second layer of network) forward their data packets to the selected nodes of first layer. These collected packets from second layer nodes by first layer nodes are directly sent to BS. In the same way, CHs of second clustered layer (third network layer) have the decision maker (DM) nodes that are in their communication range.

Data is sent to these nodes to further pass it on to the way to BS. Same fashion of communication of data packets is followed by all the CHs of subsequent layers in order to make the data packet reachable to BS.

5.2.2 Cluster Head Rotation

One of the most energy squeezing process in cluster based network architecture is a cluster head rotation. In this process, the role of being the head of the cluster is transferred to the most suitable node that has better measurement of selection metric among its competitors. In the homogenous network, each node has the same probability to become CH in the first iteration if the decision metric is from the homogenous factors. Let a node i in a network, which has the probability $\rho_i = \frac{1}{\pi r^2 \sigma}$ to become the cluster head. Where σ is the nodal density that is $\frac{T_n}{T_a}$ while T_n= total number of nodes in network and T_a= total area of network. In our case, if $T_n = 300$ and $T_a = 300\text{m x } 300\text{m} = 90000\text{m}^2$ then $\frac{300}{90000} = 0.0033\ \text{nodes/m}^2$. Energy depletion, converting the optimality to non-optimality, malfunctioning, and entrapping are usually the key causes of CH rotation. For resolving this issue, some algorithms re-initiate complete clustering process as was performed for the first time. While other randomly select the node among the neighbors of cluster head and redesign its cluster. Our Energy efficient Cluster Head Rotation Technique (ECHeaRT) rotates the cluster head designation without disturbing the cluster size and its members. Also the accessing method of CM nodes to the CH is adaptive. It may change from direct hop to multi-hop and vice versa. The proposed solution defines a threshold level for the CH energy. In case the minimum number of hops to BS is considered for the election of cluster head in cluster head rotation process then there is maximum possibility that the nodes closest to the base station are elected again and again. Also in a cluster, all the member nodes have almost same hop count to BS. Hence, residual energy of the node seems to be the most suitable choice as a decision metric for the cluster head in this underlying scenario. So, in order to achieve the distinguished energy awareness in cluster head rotation by ECHeaRT, threshold levels for CH energy are exploited in two steps:

i) Load Balancing Threshold (LBT); balancing the load on CH with the Backup Forwarding Node (BFN) when energy level reaches almost 50% of the initial energy. This initial energy is noted when node is designated as CH.

ii) Role Transfer Threshold (RTT); transferring the role of being CH from existing CH to the new CH (previously working as BFN) when the energy level approaches about 20% of the initial energy. This initial energy is noted when node is designated as CH.

Depiction for switching of CH on different roles based on its energy threshold levels is given in Figure 5.2. On reaching $E_c = \frac{E_i}{2}$ (Current energy of node that is equal to half of the initial energy of node) i.e. LBT status, switching function triggers to change the role of 'CH' to 'CH with shared load'. CH Rotation message $Msg(CHR_{init})$ is initiated from CH towards CMs to get their energy levels. Since the decision metric for the selection of next CH is highest energy carrying node. So, on the basis of collected data next potential cluster head is decided by the existing CH i.e. termed as Backup Forwarding Node for now until complete assignment of role of CH. Decision is communicated to the selected node and the acknowledgement is received. The cluster member nodes that receive this acknowledgement directly from the newly decided CH (BFN) send their data packets to it while the other member nodes of the same cluster still keep on communicating their data to the existing cluster head.

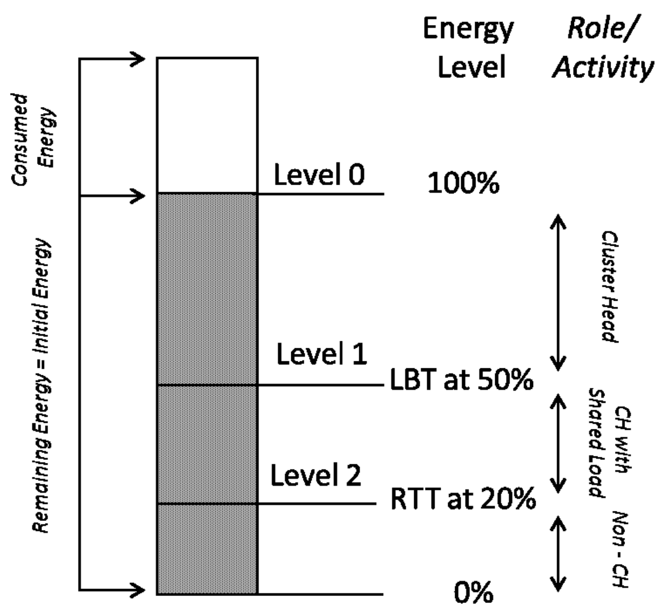


Figure 5.2: Switching of CH on Different Roles based on its Energy Threshold levels

On reaching $E_c = \frac{E_i}{5}$ i.e. 20% of the initial energy of node (RTT level), existing CH broadcasts a message to its member nodes to communicate the info of 'role transfer to BFN'.

In this scenario, two cases exist:

Case I: If all CM nodes have direct access to CH.

In this case, the notification of existing CH regarding its role transfer to BFN is directly listened by all CM nodes. These CM nodes set their CH field with the newly designated CH and later on communicate their data to it for aggregation.

Case II: If some nodes have indirect (multi-hop) access to CH and other have direct (single-hop) access.

Since, ECHeaRT offers both direct and multi-hop access of CM nodes to the CH. For the multi-hop communication, the intermediate node between the transmitting CM and the targeted CH communicate the new CH decision to its linked CMs. This node then sets its CH field to this newly designated CH and communicates with it. The other nodes which have direct access to existing CH listen the role transfer decision directly and set their CH field to this new one. With this, existing CH is demoted to non-CH node i.e. CM and BFN is promoted to CH.

In this new setup, the cluster size and its cluster members remain the same. The only consumption of energy is in CH role transfer and in communicating this decision to the cluster members.

5.3 EAR4MCDA: Energy Aware Routing Strategy (EAR) for MCDA

In the proposed scheme; Energy Aware Routing Strategy, status of node is switched between different roles due to the rotation of 'Forwarding Node' designation during inter cluster routing process. This is performed to save the network from partitioning and to prolong the network life time. In sensor network, such strategies are appreciated which utilize maximum network node (also called network utilization) with maximum delay in death of first node. This shows balanced behavior of algorithm over network nodes and less danger of creating the void due to network partitioning as well. Rotation of designation of being CH is one of the initial steps towards it. The roles of switching in four various designations are Decision Maker Node (DM_{Node}), FN, BFN and Non Forwarding Node (NFN). Subsequent paragraphs briefly explain these roles.

a) **Decision Maker Node:** The first elected FN by the CH is always from the list of DM_{Node} and satisfies the following condition;

$$DM_{Node} \rightarrow FN = Cntr_{n(i)} > Cntr_{n(j)} \quad \forall_j \quad and \quad \left| D(N_i - N_{j)} \right| \leq r_i \quad \forall_j$$

$$Where \quad j = 1,2, \dots, n$$

i.e. Node having highest neighbor count, $Cntr_{n(i)}$ among its competitors (nodes in its communication range, r_i) is promoted from DM_{Node} to FN. While DM_{Node} are from FNS listed at CH of layer 2.

b) **Forwarding Node:** The Node that is elected to pass on the received packet toward BS is called as forwarding node. Node with any of the role from BFN, NFN or DM_{Node} can be upgraded to FN after winning some defined competition at various level of operations.

$Case\ I: DM_{Node} \rightarrow FN$

$Case\ II: BFN \rightarrow FN$

$Case\ III: NFN \rightarrow BFN \rightarrow FN$

c) **Backup Forwarding Node:** This node shares the load of FN on reaching its energy at LBT threshold. The BFN is later upgraded to FN once its accompanying FN is degraded to NFN. In start, the node that satisfies the following condition is selected as BFN. Promotion of NFN to BFN follows the similar energy priority rule.

$$BFN \rightarrow FN = E(N_i) > E(N_j) \quad \forall_j \quad and \quad |D(N_i - N_{j)}| \leq r_i \quad \forall_j$$

$$Where \quad j = 1,2, \dots, n$$

i.e. Node having highest energy among its competitors is promoted from BFN to FN.

d) Non-Forwarding Node: The DM_{Node} which has once acted as FN and finished its turn of being FN is termed as NFN. Also the node which is neither a FN nor BFN or DM_{Node} is given the name of NFN. The promotion of NFN to BFN only arises when CH does not leave any DM_{Node} unelected as FN in its FN list.

NFN is upgraded to BFN and later to FN on reaching specified condition.

$$NFN \rightarrow BFN \rightarrow FN$$

Step 1:

$$NFN \rightarrow BFN = E(N_i) > E(N_j) \quad \forall_j \quad and \quad |D(N_i - N_{j)}| \leq r_i \quad \forall_j$$

$$Where \quad j = 1,2, \dots, n$$

i.e. Node having highest energy among its competitors is promoted from NFN to BFN.

Step 2:

$$BFN \rightarrow FN = E(N_i) > E(N_j) \quad \forall_j \quad and \quad |D(N_i - N_{j)}| \leq r_i \quad \forall_j$$

$$Where \quad j = 1,2, \dots, n$$

i.e. Node having highest energy among its competitors is promoted from BFN to FN.

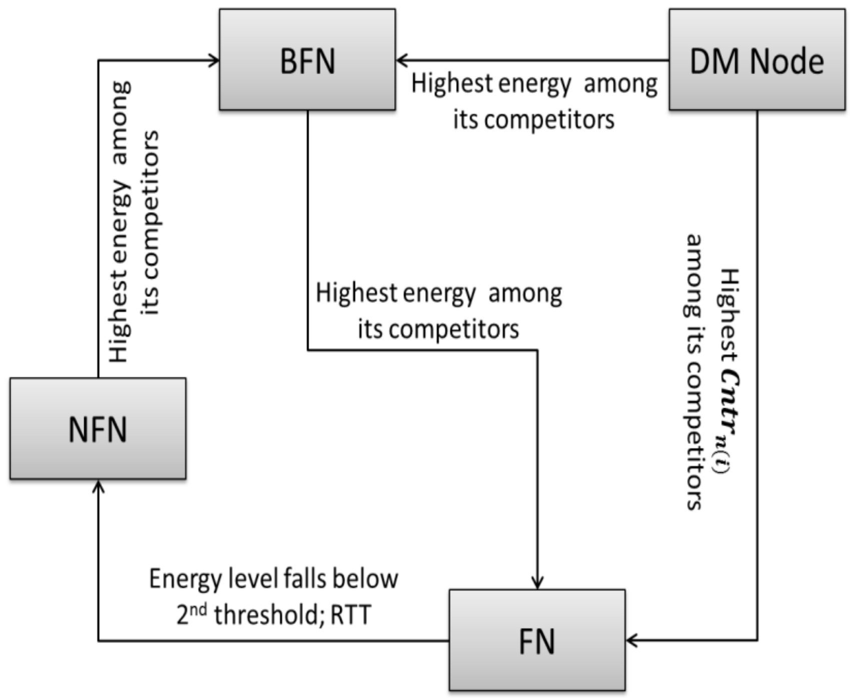


Figure 5.3: Different Roles of Network Nodes in Rotation of Forwarding Node

In view of the above discussion, we can briefly summarize the working of EARS as follows:

Cluster member nodes communicate their collected data to the cluster head. Like all other nodes of underlying layer, under discussion CH also has forwarding node table that has node IDs of its decision maker nodes (DM_{Node}) in the precedence level of their node degree. Node at the top in the list is selected as the forwarding node (FN). If this forwarding node is not the CH then it directs the data to its CH. In other case CH sends the collected data to the 'node with highest node degree carrying value' from its neighbor table. This process continues until data is collected at the BS. Figure 5.4 depicts these intra-cluster and inter-cluster routing processes in more understandable form.

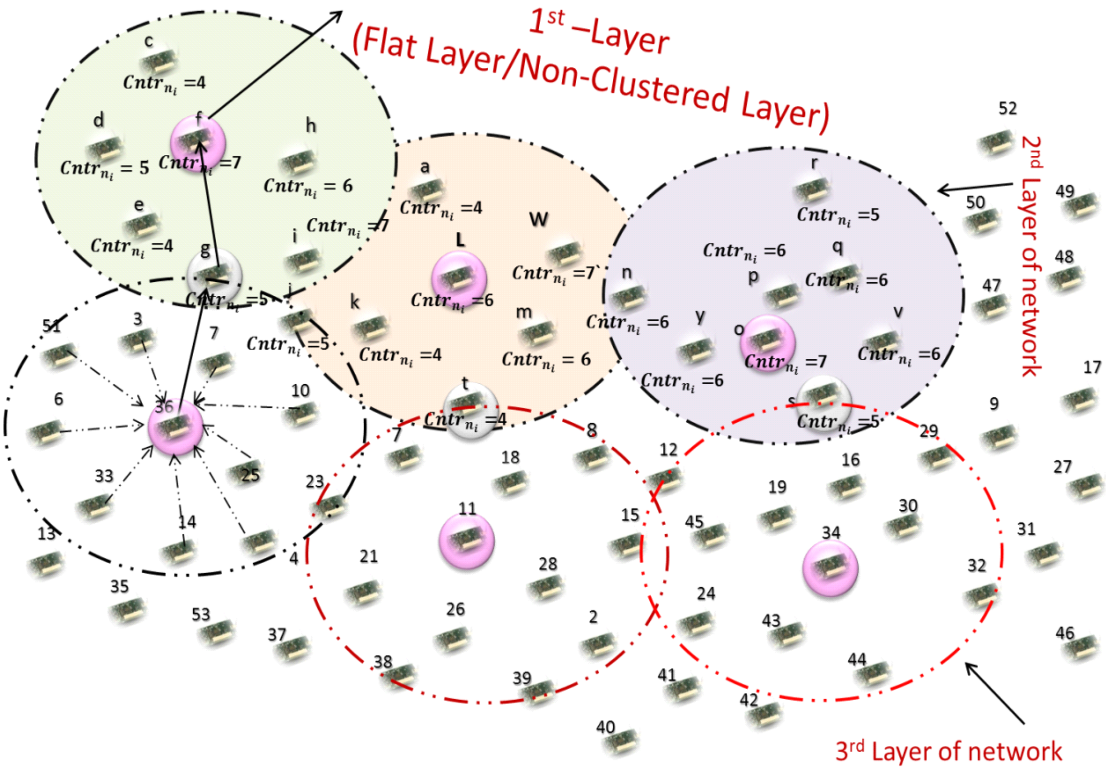


Figure 5.4: Intra-Cluster and Inter-Cluster Routing in E-MCDA Network

Rotation of FN follows the same process as is discussed for the CH rotation process. Two threshold levels are defined for the rotation of FN as is depicted in Figure 5.5.

At level 0, node is working as FN until level 1 where the energy of node is decreased to 50% of the node's initial energy. On approaching level 1, FN broadcasts $Load\_Sharing\_Msg$ message. Recipient nodes of this message decrease the transmission load towards this node to half i.e. alternate packet are transmitted to it. Remaining half transmission is directed towards next highest node density carrying node that is called as BFN. On approaching level 2 i.e. about 20% of the initial energy, transmission is totally directed towards BFN since its status has already been upgraded to FN and previous FN is demoted back to simple network node. This same process is used for the rotation of forwarding node throughout the network.

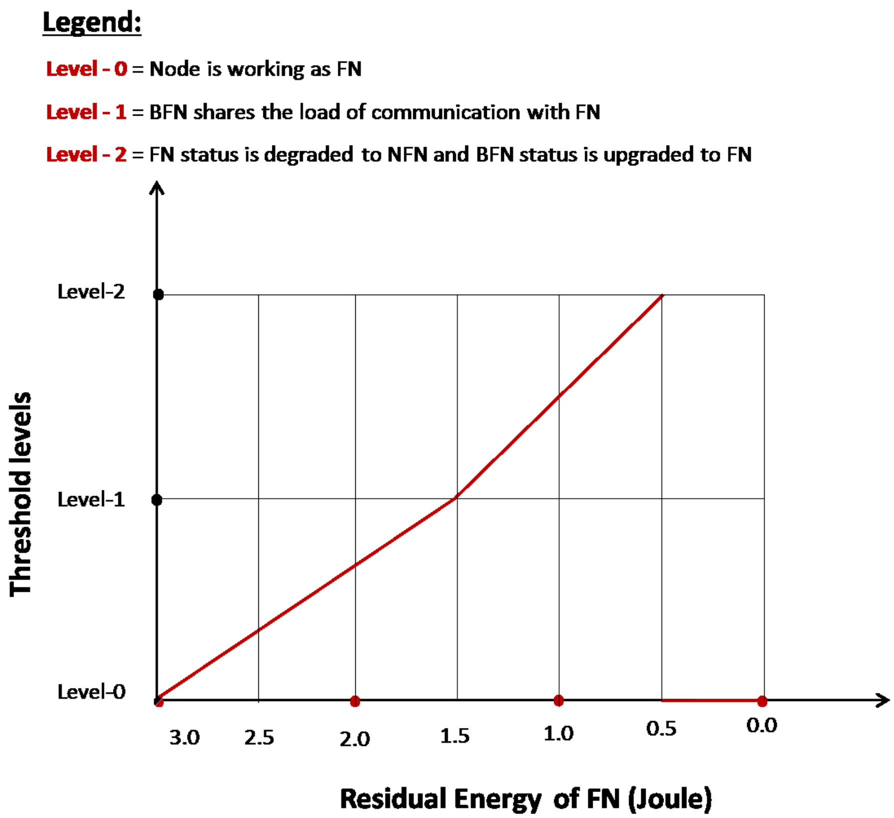


Figure 5.5: Operation of Threshold Levels in Rotation of Forwarding Node

In the subsequent subsection, feature analysis of proposed routing scheme over the proposed network architecture is given in brief.

5.4 Comparative Analysis of Proposed Solution with EADUC and TLPER

Though presented ideas related to cluster designing, cluster head selection, nodes affiliation to CH as CM, forwarding node selection, inter cluster and intra-cluster routing, and cluster head rotation, that all combine with the name EAR4MCDA; Energy Aware Routing for Multilayer cluster designing architecture, yet there are close similarities with some existing techniques in one functional aspect or the other. For this very reason, we have selected

TLPER and EADUC for the performance evaluation comparison of our proposed technique. For the working of both the algorithms, we have given sufficient details in the literature survey section. Authors of TLPER compared its performance with LEACH on Energy consumption per node, cluster head, and assistant cluster head, network utilization, and load balance effect on energy consumption. Where it outperforms its competitor; LEACH. Performance of EADUC on network life time is compared with EEUC, LEACH-M, LEACH and HEED and the authors found it better on this aspect in comparison to its competitors. In this section, a comprehensive discussion is made on the comparative analysis of EAR4MCDA with state-of-the-art related algorithms; TLPER and EADUC based on following performance metrics.

- Energy Consumption in Cluster Designing
  - Before the start of the operational phase of the network, it needs to be setup for it. We have measured the energy that is consumed in designing the clusters i.e. making the network ready for the operational phase.
- Energy Consumption in forwarding Node selection
  - Current node needs to select a node in its neighbor for pushing the data ahead to BS. That selected node is termed as forwarding node. We have measured the energy consumption that is used in information communication for the selection of forwarding node.
- Energy Consumption for one packet from source to destination
  - This energy measurement is directly related to the routing part of the algorithm. We have calculated energy that is consumed for dissemination of generated data at a far distant network node until BS. Other aspects of

energy consumption are also included in it e.g. forwarding node selection, etc.

- No. of Designed Clusters
    - Total numbers of clusters that are designed in the network.
- Average number of hops from End to End
    - The nodes are deployed randomly, and the network makes the shape of Voronoi diagram. This results in variable End to End (E2E) distance and so the variable E2E number of hops. We have taken the average of these E2E number of hops as part of performance metrics list.
- Number of packets produced in first 60 seconds after cluster formation
    - During the network operation phase, we have measured the number of data packets produced in first 60 seconds. This performance metric is used with generated throughput in first 300 seconds.
- Throughput in first 300 Seconds
    - Successful delivery of data packets is also taken as another performance evaluation parameter. We have measured the throughput in first 300 seconds of network operation phase.
- Energy Consumption for Total Throughput in First 300 Seconds
    - We have calculated the consumption of energy for successful reception of data packets at BS in the first 300 seconds of the operational phase.
- Energy Consumption at Cluster Head Rotation

- Energy consumption at CH rotation encompasses all the activities that are undertaken from time of rotation of CH until this designation is completely transferred to a new node.

We have run the simulation number of times with 500 nodes in the area of 500m x 500m. The succeeding results from Figure 5.6 to Figure 5.16 are the average of a number of executions. Simulation parameters are given in Table 5.2.

Table 5.2: Simulation Parameters

Parameter	Description
Routing Protocols	EADUC, TLPER, EAR4MCDA (Proposed)
Simulation Area	500m x 500 m
Simulator	NS 2.31
Data Rate	4 Packets/Sec
TCP/IP Layer	Network Layer
Node to Node Distance	Random
Node Type	Homogenous
No. of Nodes	500
Propagation Model	Two ray ground
Initial Energy of Node	3J

Contribution of node energy in the data routing process starts from cluster designing process and ends at approaching the data at Sink. Figure 5.6 elucidates that the cluster designing part is an indispensable phase in considering energy aware routing. In a network of 500 nodes in the area of 500m x 500m, about 41 joule energy is consumed in just designing of clustered network while implementing EADUC algorithm. Its consideration matter is reflected more on comparing the energy consumption of three competing algorithms during the cluster designing process (Figure 5.6).

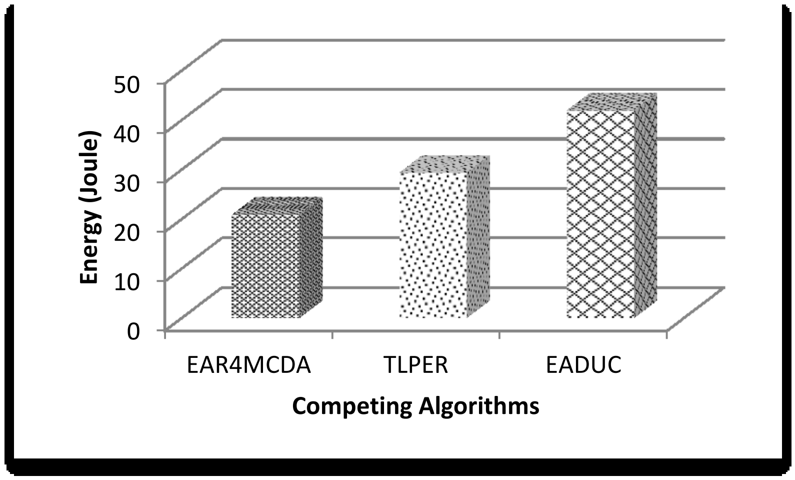


Figure 5.6: Total Energy Consumption in Cluster Designing

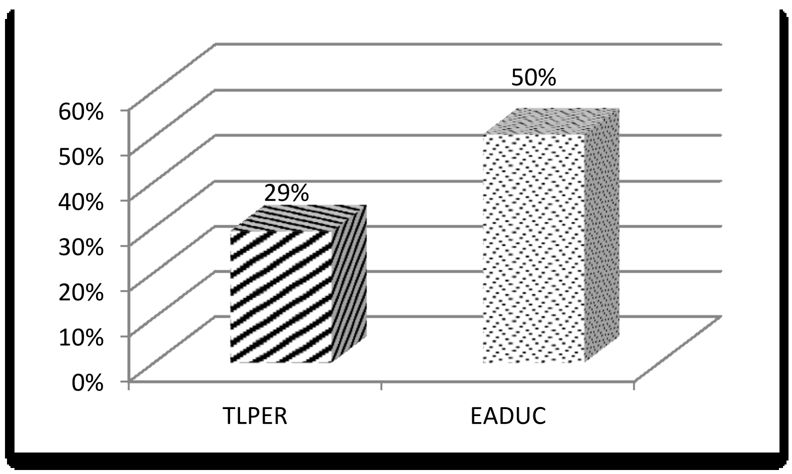


Figure 5.7: Performance Efficiency of EAR4MCDA over Competing Algorithms in Total Energy Consumption

Figure 5.7 demonstrates this effect with 29% better performance of proposed algorithm over TLPER and 50% over EADUC. Intra-cluster and inter-cluster routing makes this sensed data possible to reach the destination to end the routing. Energy efficient selection of forwarding node plays the vital role in overall energy aware routing process. Since the decision of this selection has its effect over path length, node congestion, throughput and consequently energy conservation. In this underlying research article, we have evaluated the selection of FN with respect to energy consumption only. Figure 5.8 shows the competitive energy consumption factor in forwarding the data to FN.

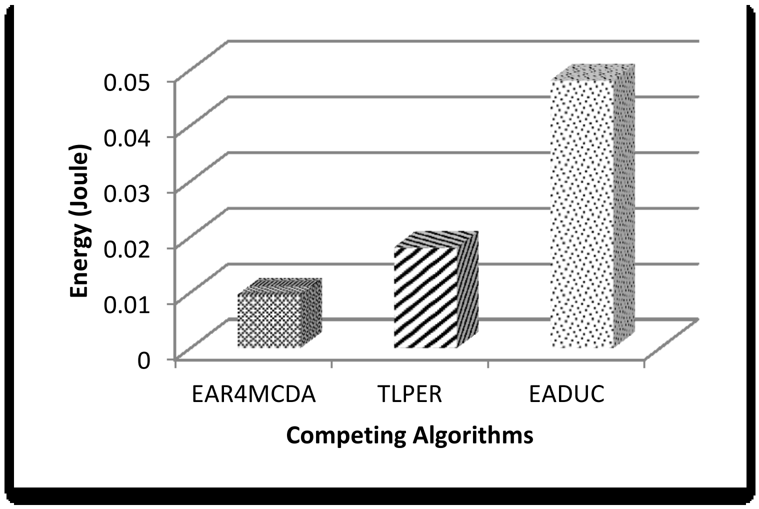


Figure 5.8: Average Energy Consumption in Forwarding Node Selection

EAR4MCDA presents an amazing idea of having a list of selected FN (three in precedence) at each node during the cluster designing process, so no extra energy conservation at this point. While in case of TLPER and EADUC, each node that intends to forward the packet needs to collect decision metric information from its neighbor nodes. From this FNS, the most suitable node having highest precedence of decision metric is selected (vicinity head in case of TLPER). This all process really squeezes node's energy that deteriorates the overall performance of the algorithm. It is ultimately reflected in the form of higher energy consumption. In this regard, performance of EAR4MCDA is 39% and 80% better than TLPER and EADUC respectively. On comparing the performance of TLPER and EADUC, we come up with the result of 68% outperform of the former over later. In TLPER, FNS may comprise of next CH, Assistant CH, and BS. Current node selects any one among them that is in reach and communicates the data to it. While in case of EADUC, current CH disseminates a query message among its neighbor nodes and collects their distance to BS and their energies. If more than one node has the same proximity to BS then, their residual energy is taken to break this tie.

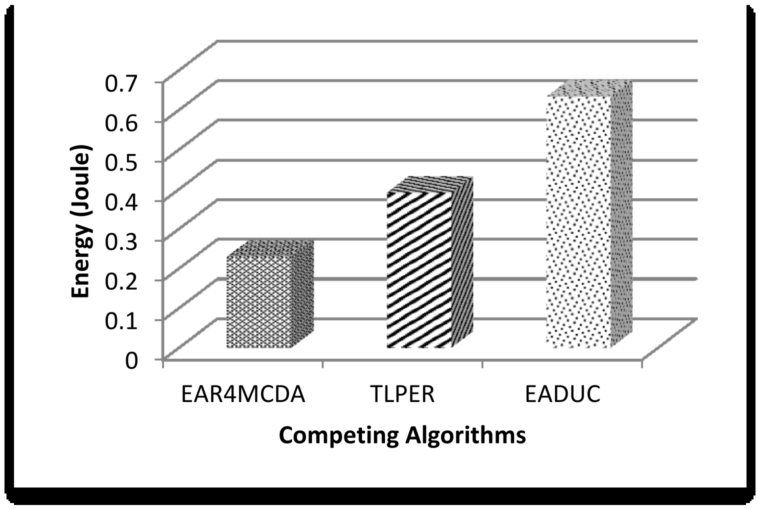


Figure 5.9: Average Energy Consumption for one Packet from End to End

Effect of this high energy consumption in FN selection makes the overall communication expensive, since FN in the path makes up a route for packet dissemination from source to sink. Figure 5.9 illustrates this point. Expensive FN selection in EADUC comes up with more costly communication of a data packet from the end to end. In graph, resultant value bar for EAR4MCDA is far smaller than that of EADUC due to the aforementioned reason. Though the path length and other factors also matter, yet to make a fair comparison, these calculations are taken for the same path length. As network size, deployment area and node deployment style are almost same. So, the number of designed clusters must positively be same but different cluster designing strategies of these algorithms make the difference. In EAR4MCDA, first layer that covers about 50m – 70m area does not have cluster that's why it is termed as flat layer. In the remaining area, cluster size is almost same. In the case of TLPER, proximity of the node to CH that is based on RSSI (Received Signal Strength Indicator) defines the cluster size. While in case of EADUC, cluster size is directly related to proximity to BS. Lesser the distance of the cluster to BS, smaller is its size and vice versa. Based on the above discussion, the highest number of cluster in EADUC compared to TLPER and EAR4MCDA is logical. This comparison is depicted in Figure 5.10.

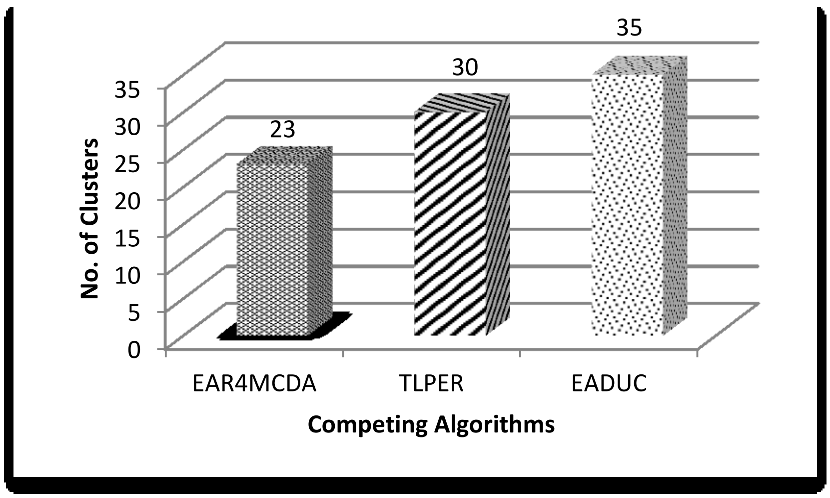


Figure 5.10: No. of Designed Clusters

In an extension to the previous discussion, it can be construed that number of clusters may mean number of end to end hops. However, this again depends upon the inter-cluster and intra-cluster routing strategies. Aggregated data at CH is sent to any next hop neighbor node which is closest to the BS. While in TPLER, inter-cluster and some cases intra-cluster communication is multi-hop, so number of hops in any related communication path in case of EADUC and EAR4MCDA Figure 5.11 gives backing to these points. This more number of hops from source to destination also increases the end to end delay. Coming back to Figure 5.9 and correlating its result with Figure 5.10 and Figure 5.11, we can intuit that forwarding node selection has its vital role in energy conservation and so in energy aware routing.

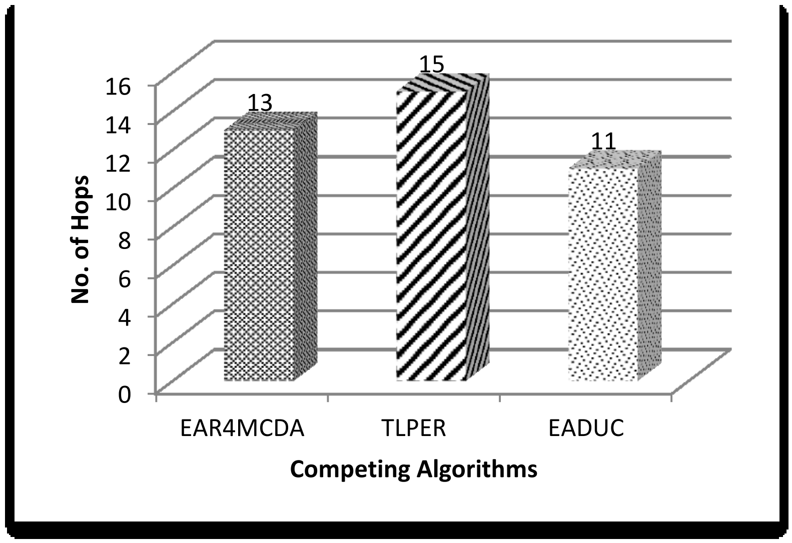


Figure 5.11: Average No. of Hops from End to End

Throughput is another important scale of measuring the efficiency of routing protocol. Number of packets production at source node does not mean the increased throughput. Moving one step back to this point, more clusters may mean more numbers of packets production.

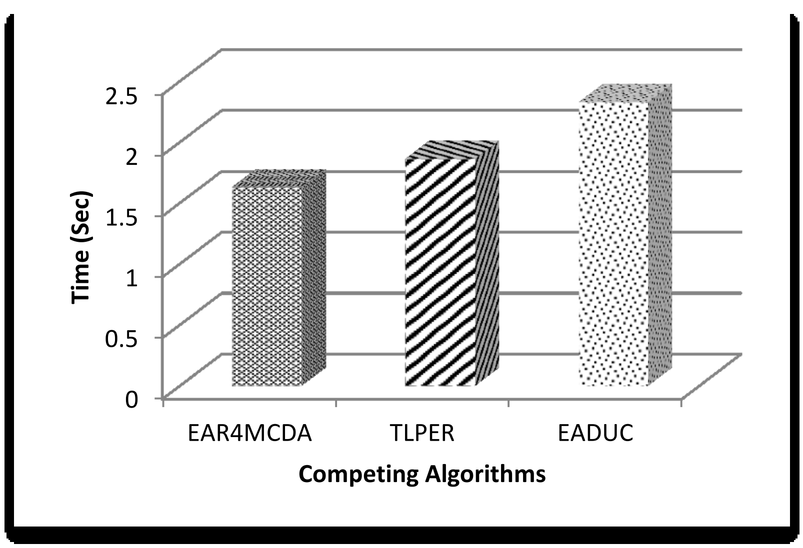


Figure 5.12: End-to-End Packet Delivery Time

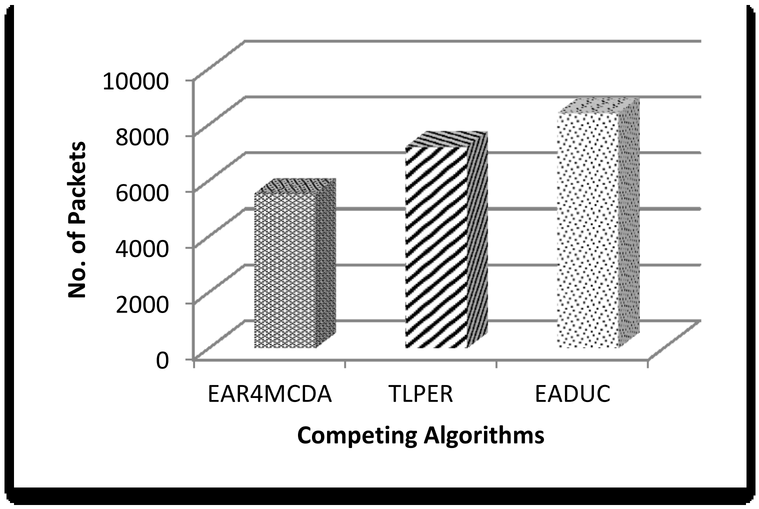


Figure 5.13: No. of Packets Produced in First 60 Seconds after Cluster formation

Let there is a scenario of 100 nodes. If there are 5 clusters and on an average each cluster may comprise of 20 nodes. The estimated waiting time for a node to communicate its data to the cluster head is equal to 19 or 20 time slots under TDMA MAC protocol. If the data rate is 4 packets per second then, at least 20/4=5 seconds are required to complete 1 cycle. During this time of 5 seconds, 20 packets are expected to produce by keeping all other things constant. Since clusters' working is parallel and not in series, so the number of packets that are produced in 5 clusters is (5x20) 100 packets. In another comparative scenario of 10 clusters with 10 nodes in each cluster with same data rate and same conditions as in the previous scenario. So, 2.5 seconds are needed to complete one cycle with the production of 10 packets and in 5 seconds 20 packets in cluster. So 200 packets (20x10) are produced at maximum in an ideal case in this scenario. So, based on these two scenarios, number of packets production in EADUC compared to TLPER and EAR4MCDA is logical. However, more packets production does not mean better throughput. Figure 5.14 plots the results of throughput in first 300 seconds. Graph represents priority of EAR4MCDA over TLPER and EADUC with the performance efficiency of 33% and 30% respectively. The very apparent reason of this outperformed result is more on FN selection in a complex way that gives rise to queue longer at node's buffer and hence more node delay leading to increased end to end delay. This may further result in more packet loss and so the decreased throughput (Figure 5.14).

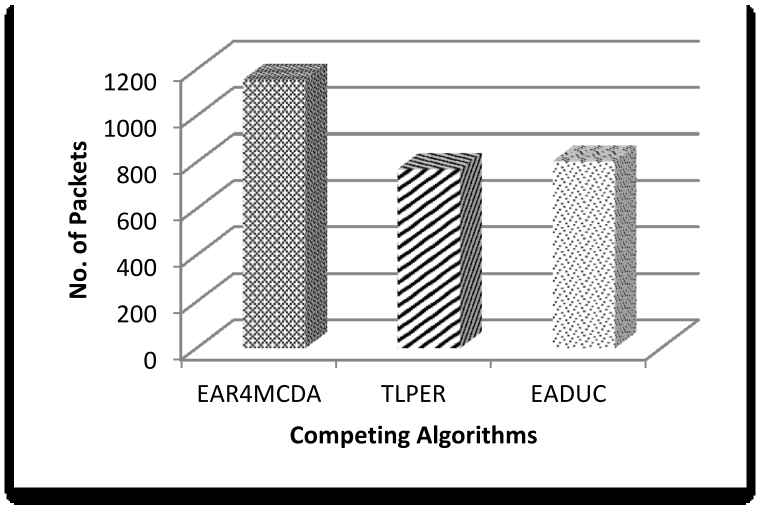


Figure 5.14: Throughput in First 300 Seconds

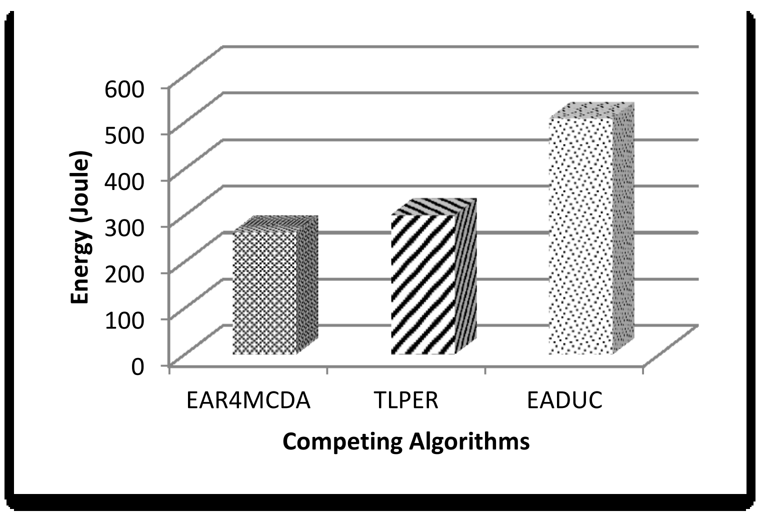


Figure 5.15: Energy Consumption for Total Throughput in First 300 Seconds

This overall reflects poor network performance with non-energy aware routing. Figure 5.15 shows the energy consumption for a total throughput for the first 300 seconds. We have also evaluated the performance of competing algorithm on energy consumption at CH rotation parameter that is depicted in Figure 5.16.

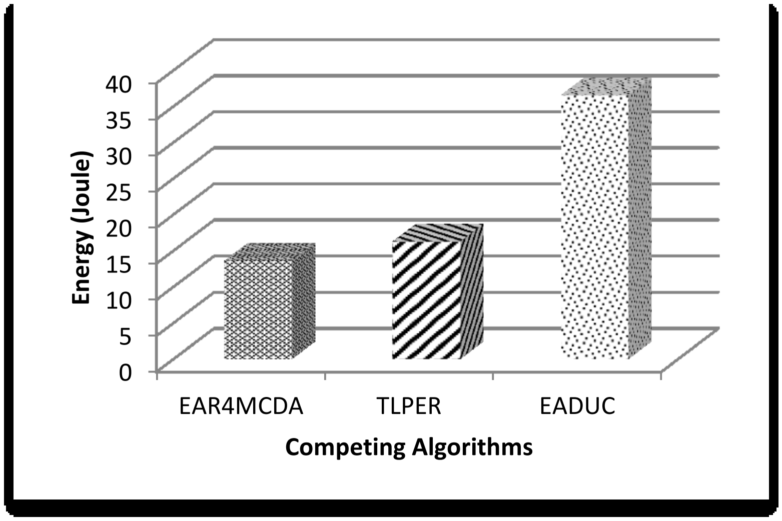


Figure 5.16: Energy Consumption at Cluster Head Rotation

EADUC does completely new designing of clusters on each round that increases its energy consumption value at CH rotation process while TLPER is to transfer CH role to the already selected assistant CH node. Almost same procedure is followed in EAR4MCDA. This makes a clear differentiation between the energy consumption performances of EADUC with other two. EAR4MCDA and TLPER consume an almost same energy.

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Chapter 6

6 Conclusions and Future Work

6.1 Conclusions

Lifetime improvement of wireless sensor networks is indispensable for making the life easy in a lot of surveillances, monitoring, tracking, etc. applications due to stringent constraint energy resource. Broadcasting and message exchange during various processes at network set up and network operational phases like cluster design, forwarding node selection, route discovery, cluster head rotation, etc. must be controlled in ingenious manner for energy aware routing. Clustered network is proved to be the most energy efficient network design. This network design is customized for life time improvement of WSN. A workable solution, *Multilayer Cluster Designing Algorithm* (MCDA), for the most energy demanding part of the cluster based wireless sensor networks is introduced which is innovative in its design and communication architecture. Results of our experiments of MCDA have shown that it has outperformed the two prevailed cluster based network architectures; CCD and DCD. The key performance evaluation parameters taken for this comparison were energy consumption in various operational parametric values, number of packets broadcast and number of clusters designed. It has been proved from the simulation experiments that Energy consumption in CCD is an exponentially increasing function of network size while keeping the deployed number of nodes same. In the case of DCD, it does not have a big effect by the network scale in the same scenario. Introduction of $P_{(Seq\_no)}$, selective listeners' response, limited and optimized competing $Node_{(dm_{id})}$ and reduced cluster head candidates have played their vital role in gaining the maximum advantage from the clustered network to improve the network life time of homogenous wireless sensor network. Energy conservation level of MCDA is 26% higher in MSN and 47% in LSN compared to TLPER (CCD). While in comparison to V-LEACH and EELBCRP (DCD), the outperform results of MCDA regarding energy consumption are 30% and 32% respectively in MSN and 19% and 22% respectively in LSN. During the clustered architectural design process the messages exchange is one of the big source of maximum energy consumption. Regarding the comparison in case of number of packets broadcast as a performance evaluation parameter, proficiency of MCDA is better than TLPER with the percentage of 36 in MSN and 58 in LSN. Whereas competing with EELBCRP and V-LEACH (DCD), MCDA has shown better performance with the priority value of 41% and 43% respectively in MSN and 33% and 34% respectively in LSN. Hence, it is demonstrated from the experimentation and detailed analytical discussion that MCDA is a priority choice for clustered network design in MSN as well as LSN in comparison to centralized and distributed cluster design architectures.

Idea of MCDA was improved with novel algorithms for time slot allocation at network setup phase to make the cluster designing process more energy efficient, energy efficient cluster head selection, and ‘Required Node Degree’ based cluster member selection for near equal size clusters. We named it Extended MCDA. These ramifications play vital roles to achieve the target. Results of our experiments have shown that E-MCDA has outperformed the two competitive mechanisms. The key performance evaluation parameters taken for this comparison were energy consumption in various operational parametric values at per node level and at layer level, no. of packets broadcast, no. of clusters designed, number of members per clusters and number of un-clustered nodes. Acceptance of E-MCDA over MCDA and EADUC in aforesaid performance evaluation parameters has been proved from the simulation based experiments. Since total energy conservation level of E-MCDA is 68% higher compared to EADUC. While in comparison to MCDA, the outperform results of MCDA regarding the same is 17%. During the clustered designing process, the messages exchange is one of the big sources of maximum energy consumption. Regarding the comparison in case of no. of packets transmitted as a performance evaluation parameter, proficiency of E-MCDA is better than EADUC with the percentage of 69. Whereas competing with MCDA, E-MCDA has shown better performance with the priority value of 19%. We have also done a comparison of energy consumption in cumulative. As in E-MCDA and MCDA nodes grouping is made into layers i.e. flat layer N_{L_1}, clustering layer 1 N_{L_2}, clustering layer 2 N_{L_3} etc. So, in accordance with this scenario of layering of nodes, cumulative energy consumption in EADUC is calculated in the same way. Hence, it is demonstrated from the experimentation and detailed analytical discussion that E-MCDA is a priority choice for clustered network design. The comprehensive and detailed, analytical and empirical comparative analysis of E-MCDA with its parent idea; MCDA and another state-of-the-art technique; EADUC has also evidenced the achievement of our research goals to propose an energy efficient algorithm for the most energy demanding part of cluster based wireless sensor networks.

Since, network performance is the accumulative effort of a number of integral and integrated steps so after strengthening the preliminary step of cluster designing with MCDA, a mechanism; EAR4MCDA was proposed. This idea is an endeavor to ameliorate the network performance from energy consumption aspect in the routing process.

Architecture of MCDA was exploited for FN selection, Inter and intra cluster routing, cluster head rotation and all the way to make this overall process energy aware. Empirical results intuit that careful and foresighted selection of FN leads to energy efficient intra-cluster and inter-cluster routing that accumulate to give energy aware routing. It is also construed from the results that though more clusters may produce number of packets, yet other favorable factors are there to come up this more production into improved throughput. Otherwise, it is just a burden on network and results in increased congestion, more packet drop ration, more end to end delay and hence more energy consumption is needed to alleviate these issues and to maintain the network performance. It is also deduced from the experiments that cluster head rotation on each round is not a sensible choice to implement rather letting the CH to work until a specified level of its energy, and then rotate its designation to some other suitable node.

6.2 Future Work

Our work can be extended in many aspects starting from the proposed network architecture until energy aware routing process. Changing the selection parameter for various roles of nodes, introducing the node heterogeneity for Decision Maker Nodes, CHs, or others and the induction of localization techniques can improve the work at various aspects. Also the proposed multi-layer design can be tested for other issues like Hotspot. Keeping in view the flexibility of proposed mechanism, some of the extension in this work are suggested as follows.

The performance of first flat layer of E-MCDA can be compared to unequal clustering algorithms which have smaller cluster size in the neighbor of BS to lessen the network load over these nodes. The same goal of achieving the higher network life among the two techniques motivates for such sequence of comparative studies. In case of heterogeneous network, the same idea of multi-layer network design can be tested with changing the cluster head election criteria such as ratio of residual energy of the node to the average energy of the neighbor nodes [138] or energy welfare formula [137] etc. In our idea of Multi-layer design, although we tried to present the pure network layer algorithm, so the involvement of any localization algorithm or GPS enabled nodes is kept away. Yet another induction of idea can be defining the layer boundaries by transmitting the broadcast signal with varying defined levels as is used by Jabbar *et al.* [101]. This will further decrease the packets broadcasting that are used for selecting the decision maker nodes at the boundary of layers. More-over, the proposed algorithms for throughput maximization can also be used in non-conventional routing algorithms [162]. Many interdisciplinary ideas relating to bio-inspired computing are briefly given in [163] that can also be used to further extend and improve the proposed work given in Chapter 5. We believe that the proposed multi-layer network design can optimistically handle the hotspot issue that exists usually in sparsely deployed sensor networks. This extension of our work can be a good contribution in related work.

In case of very large network, nodes in neighborhood of BS become more overburdened due to acting as transient node for communication the network data to BS. It increases the chances of rapid depletion of these nodes' energy. In our proposed scenario, flat layer is comprising of nodes that are in one hop distance from BS. In case, flat layer size is increased up to two hops from BS, It will increase message overhead, but on the other hand, it helps in giving better solution to hop spot issue. Setting a tradeoff between flat layer size for better solution of hotspot for improving the network lifetime and arising message overhead due to it can be another future work.

The proposed mechanism can also has its application in densely deployed WSN for energy aware big data gathering. Similar approach based on pure clustered network is proposed in [164]. Same idea can also be exploited in large deployment of nodes (uniquely identifiable embedded computing devices) that are attached to things and are interconnected to each other over the existing infrastructure of internet. This concept is termed as Internet of Things (IoT) [64]. IoT is comparatively new and innovative concept encompassing number of emerging technologies where WSN is core among those.

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References

[1] M. CrossBow, "Mood CrossBow," 2014. [Online]. Available: http://xbow.com/. [Accessed 4 August 2014].

[2] "MicaZ Data Sheet," Cross bow Technology, Inc ., 2 February 2007. [Online]. Available: http://www.openautomation.net/uploadsproductos/micaz_datasheet.pdf. [Accessed 27 July 2014].

[3] L. Wang and Q. Xu, "GPS-Free Localization Algorithm for Wireless Sensor Networks," *Sensors,* pp. 5899-5926, 2010.

[4] X. W. G. C. Xiaojun Zhua, "Relative localization for wireless sensor networks with linear topology," *Computer Communication, Elsevier,* 2013.

[5] A. Couteau, O. Labs, F. Meylan, F. Evennou and D. Cibaud, "Anchor-Free Absolute Localization and Tracking System for Wireless Sensor Networks," in *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, Yokohama, 2011.

[6] "The Sensor Network Museum," TIK WSN Research Group at ETH, Zurich, 2014. [Online]. Available: http://www.snm.ethz.ch/. [Accessed 15 August 2014].

[7] "BTnodes - A Distributed Environment for Prototyping Ad Hoc Networks," ETH Zurich, 2007. [Online]. Available: http://www.btnode.ethz.ch/. [Accessed 16 August 2014].

[8] "EyesIFXv21Node," TWIST Community Wiki, 2009. [Online]. Available: http://www.twist.tu-berlin.de/wiki/WSN/EyesIFXv21Node. [Accessed 16 August 2014].

[9] "Introducing the G-Node," SOWNet Technologies, 2014. [Online]. Available: http://www.sownet.nl/index.php/products/gnode. [Accessed 16 August 2014].

[10] "Flecktm series at CSIRO ICT Centre," TIK WSN Research Group at ETH Zurich, 2014. [Online]. Available: http://www.snm.ethz.ch/snmwiki/Projects/Fleck. [Accessed 16 August 2014].

[11] "Flecktm series," 2014. [Online]. Available: http://www.snm.ethz.ch/snmwiki/pub/uploads/Projects/Flecks.pdf. [Accessed 16 August 2014].

[12] "Anatomy of Sun Spot," Oracle Labs, Oracle Corporation, 2014. [Online]. Available: http://sunspotworld.com/products/. [Accessed 16 August 2014].

[13] "Tmote Sky," TIK WSN Research Group at ETH Zurich, 2014. [Online]. Available: http://www.snm.ethz.ch/snmwiki/Projects/TmoteSky. [Accessed 16 August 2014].

[14] "T-Nodes," TIK WSN Research Group at ETH Zurich, 2014. [Online]. Available: http://www.snm.ethz.ch/snmwiki/Projects/T-Nodes. [Accessed 16 August 2014].

[15] "Real-Time Wireless Sensor Network Platform - FireFly Sensor Networks," Real-Time & Multimedia Systems Lab, Carnegie Mellon University, 2014. [Online]. Available: http://www.ece.cmu.edu/firefly/index.html. [Accessed 16 August 2014].

[16] "Build your own wireless sensor network. Get a headstart on the internet of things (IOT).," WISENSE, 2014. [Online]. Available: http://www.wisense.in/. [Accessed 16 August 2014].

[17] S. Jabbar, A. E. Butt, Najm-us-Sehr and A. A. Minhas, "TLPER: Threshold Based Load Balancing Protocol For Energy Efficient Routing In WSN," in *The 13th International Conference on Advanced Communication Technology (ICACT'11)*, Seoul, South Korea, 2011.

[18] S. Jabbar, A. A. Minhas, R. A. Akhtar and M. Z. Aziz, "REAR: Real-Time Energy-Aware Routing For Wireless Sensor Network," in *IEEE International Conference on Pervasive Intelligence and Computing*, Chengdu, China, 2009.

[19] M. Ilyas and I. Mahgoub, Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems, 1. Edition, Ed., CRC Press, 2004.

[20] K. Pister, "Smart Dust," 2010. [Online]. Available: http://robotics.eecs.berkeley.edu/~pister/SmartDust/. [Accessed 27 July 2014].

[21] S. I. Lee, J. Y-T and E. Leung, Handbook of Real-Time and Embeded Systems, Computer and information science, 1st ed. ed., vol. 1, Boca Raton London New York: Chapman and Hall/CRC, 2008.

[22] "WSN in the real world," ZigBee Alliance, 2011. [Online]. Available: http://www.automatedbuildings.com/releases/sep11/110929102404zigbee.html. [Accessed 27 July 2014].

[23] M. Marin-Perianu, S. Chatterjea, R. Marin-Perianu, S. Bosch, S. Dulman, S. Kininmonth and P. Havinga, "Wave monitoring with wireless sensor networks," in *International Conference on Intelligent Sensors, Sensor Networks and Information Processing, 2008. ISSNIP 2008.* , Sydney, NSW, 2008.

[24] A. Alkandari, M. alnasheet, Y. Alabduljader and S. M. Moein, "Wireless Sensor Network (WSN) for Water Monitoring System: Case Study of Kuwait Beaches," *International Journal of Digital Information and Wireless Communications,* vol. 1(4), pp. 709-717, 2011.

[25] M. R. Martonosi, "The Princeton ZebraNet Project: Mobile Sensor Networks for Wildlife Tracking," 2005. [Online]. Available: http://www.cis.upenn.edu/departmental/events/abstracts-2004/marg.htm. [Accessed 28 July 2014].

[26] K. Kwong, T.-T. Wu and Goh, "Implementation of herd management systems with wireless sensor networks," *IET Wireless Sensor Systems,* vol. 1, no. 2, pp. pp. 55-65., 2011.

[27] E. H. Callaway, "NeuRFon," 1999. [Online]. Available: http://www.encyclo.co.uk/define/NeuRFon. [Accessed 27 July 2014].

[28] T. Naumowicz, R. Freemanyz, H. Kirky, B. Deany, M. Calsynz, A. Liers, A. Braendlez, T. Guilfordy and J. Schiller, "Wireless Sensor Network for Habitat Monitoring on Skomer Island," in *5th IEEE International Workshop on Practical Issues in Building Sensor Network Applications*, Denver, Colorado,, 2010.

[29] A. Alkandari, "Traffic Surveillance by Wireless Sensor Networks," PATH Research Report, California , 2007.

[30] O. Bondarenko, S. Kininmonth and M. Kingsford, "Underwater Sensor Networks, Oceanography and Plankton Assemblages," in *3rd International Conference on Intelligent Sensors, Sensor Networks and Information*, 2007.

[31] A.-J. Garcia-Sanchez, F. Garcia-Sanchez, F. Losilla, P. Kulakowski, J. Garcia-Haro, A. Rodríguez, J.-V. López-Bao and F. Palomares, "Wireless Sensor Network Deployment for Monitoring Wildlife Passages," *Sensors,* vol. 10, pp. 236-7262, 2010.

[32] R. Kacimi, R. Dhaou and Beylot, "Using Energy-Efficient Wireless Sensor Network for Cold Chain Monitoring," in *6th IEEE Consumer Communications and Networking Conference*, 2009.

[33] A. Kunnath and Ramesh, "Integrating Geophone Network to Real-Time Wireless Sensor Network System for Landslide Detection," in *First International Conference on Sensor Device Technologies and Applications*, 2010.

[34] A. Laflor-Hernandez, J. Nieto-Hipolito, M. Vazquez-Briseño, H. Cervantes-De Avila, J. Sanchez-Lopez and E. Garcia, "MMIG: A middleware for communicating a WSN to a Web site for monitoring vital signs," in *Pan American Health Care Exchanges*, 2011.

[35] G. Padmavathi, D. Shanmugapriya and M. Kalaivani, "A Study on Vehicle Detection and Tracking Using Wireless Sensor Networks," *Wireless Sensor Network,* Vols. Vol. 2 No. 2,, pp. pp. 173-185, 2010.

[36] A. Wood, J. Stankovic, G. Virone, L. Selavo, Z. He, Q. Cao, T. Doan, Y. Wu, L. Fang and R. Stoleru, "Context-Aware Wireless Sensor Networks for Assisted Living and Residential Monitoring," *IEEE Networks,* vol. 22, no. 4, pp. 26 - 33, 2008.

[37] C. Wartmann and S. Kohler, "Wireless sensor networks in sick buildings," 2014. [Online]. Available: http://www.embedded.arch.ethz.ch/Projects/SickBuilding. [Accessed 15 August 2014].

[38] T. Schmid, H. Dubois-ferrière and M. Vetterli, "SensorScope: Experiences with a Wireless Building Monitoring Sensor Network," in *First Workshop on Real-World Wireless Sensor Networks* , USA, 2005.

[39] F. Ingelrest, G. Barrenetxea, G. Schaefer, M. Vetterli, O. Couach and M. Parlange, "SensorScope: Application-specific sensor network for environmental monitoring," *ACM Transactions on Sensor Networks (TOSN),* vol. 6, no. 2, 2010.

[40] G. Barrenetxea, F. Ingelrest, G. Schaefer and M. Vetterli, "SensorScope: Out-of-the-Box Environmental Monitoring," in *International Conference on Information Processing in Sensor Networks*, St. Louis, MO, 2008 .

[41] P. M. Vetterli, "Sensorscope: Sensor Networks for Environmental Monitoring," 2013. [Online]. Available: http://lcav.epfl.ch/sensorscope-en. [Accessed 16 August 2014].

[42] D. Rus and E. Basha, "Wireless Sensor Network Provides Early Flood Detection for Underserved Countries," Microsoft Reseach, USA, 2006.

[43] S. H. Wright, "Students tackle flooding in Honduras," 2005. [Online]. Available: http://newsoffice.mit.edu/2005/honduras. [Accessed 16 August 2014].

[44] D. M. Dunbabin and M. C. Bengston, "Smart sensors monitoring water quality and catchment health," 2011. [Online]. Available: http://www.csiro.au/Organisation-Structure/Flagships/Water-for-a-Healthy-Country-Flagship/Integrated-Water-Resources-Management/smart-sensors-monitoring-water-quality.aspx. [Accessed 16 August 2014].

[45] C. Tschudin, S. Gruber, D. V. Muhll, A. Hasler and I. Talzi, "PermaSense Project home page," 2006. [Online]. Available: http://cn.cs.unibas.ch/projects/permasense/. [Accessed 15 August 2014].

[46] I. Talzi, A. Hasler, S. Gruber and C. Tschudin, "PermaSense: Investigating Permafrost with a WSN in the Swiss Alps," in *4th workshop on Embedded networked sensors*, Cork, Ireland, 2007.

[47] S. Khan, A. Abbas, T. Rana and J. Carroll, "Dairy water use in Australian dairy farms: Past trends and future prospects," CSIRO: Water for a Healthy Country National Research Flagship, Australia, 2010.

[48] D. P. Hardisty and L. Regan, "Water for a Healthy Country," 2014. [Online]. Available: http://www.csiro.au/Organisation-Structure/Flagships/Water-for-a-Healthy-Country-Flagship.aspx. [Accessed 15 August 2014].

[49] M. Ito, Y. Katagiri, M. Ishikawa and H. Tokuda, "Airy Notes: An Experiment of Microclimate Monitoring in Shinjuku Gyoen Garden," in *Fourth International Conference on Networked Sensing Systems*, Braunschweig, 2007.

[50] M. Ito, "Airy Notes," 2006. [Online]. Available: http://www.niya.net/airynotes.html. [Accessed 15 August 2014].

[51] G. Tolle, J. Polastre, R. Szewczyk, D. Culler, K. T. Neil Turner, S. Burgess, T. Dawson, P. Buonadonna, D. Gay and W. Hong, "A Macroscope in the Redwoods," in *The ACM Conference on Embedded Networked Sensor Systems*, San Diego, California, USA, 2005.

[52] S. Yang, "Redwoods go high tech: Researchers use wireless sensors to study California's state tree," 2003. [Online]. Available:

http://www.berkeley.edu/news/media/releases/2003/07/28_redwood.shtml. [Accessed 15 August 2014].

[53] G. Werner-Allen, K. Lorincz, M. Ruiz, O. Marcillo, J. Johnson, J. Lees and M. Welsh, "Deploying a Wireless Sensor Network on an Active Volcano," *IEEE Internet Computing,* vol. 10, no. 02, pp. 18 - 25, 2006.

[54] M. Welsh, J. Johnson, J. Lees and O. Marcillo, "Volcano monitoring," 2008. [Online]. Available: http://fiji.eecs.harvard.edu/Volcano. [Accessed 15 August 2014].

[55] I. F. Akyildiz, D. Pompili and T. Melodia, "Underwater Acoustic Sensor Networks (UW-ASN)," 2004. [Online]. Available: http://www.ece.gatech.edu/research/labs/bwn/UWASN/. [Accessed 27 July 2014].

[56] P. Kinney, P. Jamieson, J. Gutierrez and M. Naeve, "IEEE 802.15 WPAN™ Task Group 4 (TG4)," The Institute of Electrical and Electronics Engineers, Inc., 27 January 2010. [Online]. Available: http://www.ieee802.org/15/pub/TG4.html. [Accessed 01 August 2014].

[57] IEEE, "IEEE 802.15™: WIRELESS PERSONAL AREA NETWORKS (PANs)," IEEE Standard Association, 2014. [Online]. Available: http://standards.ieee.org/about/get/802/802.15.html. [Accessed 1st August 2014].

[58] B. Haberman and T. Lemon, "6lowpan Status Pages," 2005. [Online]. Available: http://www.6lowpan.org/Brian Haberman, Ted Lemon. [Accessed 1st August 2014].

[59] J. Sarto, "ZigBee Vs. 6LowPAN for sensor networks," 2014. [Online]. [Accessed 1st August 2014].

[60] A. Ott, "Wireless Networking with IEEE 802.15.4 and 6LoWPAN," in *Embedded Linux Conference*, Europe, 2012.

[61] M. B. Nejad, "Ultra Wideband Impulse Radio for Wireless Sensing and Identification," Electronic and Computer Systems, KTH – Royal Institute of Technology, Stockholm, Sweden, 2008.

[62] T. Ye, M. Walsh, P. Haigh, J. Barton, A. Mathewson and B. O'Flynn, "Experimental Impulse Radio IEEE 802.15.4a UWB Based Wireless Sensor Localization Technology: Characterization, Reliability and Ranging," in *The 22nd IET Irish Signals and Systems Conference*, Dublin,, 2011.

[63] I. Jawhar, M. Ammar, S. Zhang, J. Wu and N. Mohamed, "Ferry-based linear wireless sensor networks," in *IEEE Global Communications Conference (GLOBECOM)*, Atlanta, 2013.

[64] D. Miorandi, S. Sicari, F. D. Pellegrini and I. Chlamtac, "Internet of things: Vision, applications and research challenges," *Ad Hoc Networks,* vol. 10, no. 2012, p. 1497–1516, 2012.

[65] V. B. Ko and N. H. Vaidya, "Location Aided Routing," in *International Conference on Mobile Computing and Networking (MobiCom)*, Dallas, USA, October, 1998.

[66] Y.-B. Ko and N. H. Vaidya, "Location-Aided Routing (LAR) in mobile ad hoc networks," *Wireless Networks,* vol. 6, p. 307–321, 2000.

[67] D. B. Johnson, D. A. Maltz and J. Broch, "DSR: the dynamic source routing protocol for multihop wireless ad hoc networks," in *Ad hoc networking*, Boston, MA, USA, Addison-Wesley Longman Publishing Co., Inc., 2001, pp. 139-172 .

[68] C. E. Perkin and E. Royer, "Ad-hoc on demand distance vector router," in *2nd IEEE Workshop on Mobile Computing System and Appliations*, New Orleans, Louisiana, USA, 1999.

[69] J. A. Stankovic, "Wireless Sensor Networks," *Computer Magazine,* 2008.

[70] A. A. Minhas, *Power Aware Routing Protocols for Wireless ad hoc Sensor Networks,* Graz: Graz University of Technology, 2007.

[71] H. A. Gurbhej Singh, "Design and Architectural Issues in Wireless Sensor Networks," *International Journal of Advanced Research in Computer Science and Software Engineering,* vol. Volume 3, no. Issue 1, , January 2013.

[72] W. Lingming, *Physical Layer And Application Layer Issues Of Wireless Sensor Network,* The University Of Texas At Arlington, 2006.

[73] G. Shankar, T.G.Basavaraju, D. Manjaiah and K. S. Subir, "Issues in Wireless Sensor Networks," in *Proceedings of the World Congress on Engineering*, London, U.K, 2008.

[74] A. Jain, S. Deepak, G. Mohit and V. A. K., "Protocols for Network and Data Link Layer in WSNs: A Review and Open Issues," *Advances in Networks and Communications, Communications in Computer and Information Science,* vol. 132, pp. 546-555, 2011.

[75] I. S. Demirkol, *Medium Access Control Layer Performance Issues In Wireless Sensor Network,* Bo˘gazi¸ci University, 2008.

[76] A. A. Alhameed and S. G. Baicher, "MAC Layer Overview for Wireless Sensor Networks," in *International Conference on Computer Networks and Communication Systems*, 2012.

[77] P. R. Gundalwar and V. N. Chavan, "Analysis Of Wireless Sensor Networks (WSNs) And Routing Issues," *International Journal of Engineering Research & Technology,* vol. 1, no. 8, October 2012.

[78] "Routing Security Issues in Wireless Sensor Networks: Attacks and Defenses," in *Sustainable Wireless Sensor Networks*, Yen Kheng Tan (Ed.) ed., Sustainable Wireless Sensor Networks, INTECH Publishers, December, 2010, pp. 279 - 309.

[79] S. Jabbar, A. A. Minhas, A. Paul and S. Rho, "MCDA: Multilayer Cluster Designing Algorithm For Network Lifetime Improvement Of Homogenous Wireless Sensor Networks," *Journal Of Supercomputing,* vol. 11227, 2014.

[80] H. A. Nguyen, A. Forster, D. Puccinelli and S. Giordano, "Sensor node lifetime: An experimental study," in *Pervas ive Computing and Communications Workshops*, Seattle, WA, 2011.

[81] C. Wang and L. Xiao, "Improving Event-to-Sink Throughput in Wireless Sensor Networks," *Distributed Computing in Sensor Systems,* vol. 4549, pp. 50-63, 2007.

[82] A. Rahman, S. A. El and W. Gueaieb, "Wireless Sensor Network Transport Layer: State of the Art," in *Sensors*, vol. 21, S. Mukhopadhyay and R. Huang, Eds., Berlin, Heidelberg: Springer, 2008, pp. 221-245.

[83] S. Zafar, "A Survey of Transport Layer Protocols for Wireless Sensor Networks," *International Journal of Computer Applications ,* vol. 33, no. 1, pp. 44-50, 2011.

[84] Ohize and H. Ohiani, "Emerging Issues in Wireless Sensor Networks," *Journal of Software & Automation,* 2011.

[85] K. Maraiya, K. Kant and N. Gupta, "Application based Study on Wireless Sensor Network," *International Journal of Computer Applications,* vol. 21, no. 8, May 2011.

[86] S. d. Muruganathan, D. C. Ma, r. Bhasin and A. Fapojuwo, "A Centralized Energy-Efficient Routing Protocol for Wireless Sensor Networks," *IEEE Radio Communications,* 2005.

[87] H. Samet, "K-Nearest Neighbor Finding Using Max Nearest Dist," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 30, no. 02, p. 243 – 252, 2008.

[88] Y.-m. Cheung, M. Li, M. Ng and J. Huang, "Agglomerative Fuzzy K-Means Clustering Algorithm with Selection of Number of Clusters," *IEEE Transactions on Knowledge and Data Engineering,* vol. 20, no. 11, pp. 1519- 1534, 2008.

[89] M. Mahmud, M. Rahman and M. Akhtar, "Improvement of K-means clustering algorithm with better initial centroids based on weighted average," in *7th International Conference on Electrical & Computer Engineering*, Dhaka, 2012.

[90] R. Guan, X. Shi, M. Marchese, C. Yang and Y. Liang., "Text Clustering with Seeds Affinity Propagation," *IEEE Transactions on Knowledge and Data Engineering,* vol. 23, no. 04, pp. 627- 637, 2011.

[91] W. Heinzelman, A. Chandrakasan and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proceedings of the 33rd International Conference on System Sciences*, Hawaii, 2000.

[92] N. Jin, X. Lou, T. Peng, Q. Zhou and Y. Chen, "Improvement of LEACH protocol for WSN," in *9th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD)*, Sichuan, 2012.

[93] M. B. Yassein, A. Al-zou'bi, Y. Khamayseh and W. Mardini, "Improvement on LEACH Protocol of Wireless Sensor Network," vol. 03, no. 02, 2009.

[94] S. Lindsey and C. Raghavendra, "PEGASIS: Power-efficient gathering in sensor information systems," in *Aerospace Conference*, Big Sky, Montana, 2002.

[95] N. Aslam, W. Robertson and W. Phillip, "Algorithms for Relay Node Selection in Randomly Deployed Homogenous Cluster-based Wireless Sensor Networks," *Adhoc & Sensor Wireless Networks Journal, Special Issue on Sensor Technologies and Applications,* vol. Volume 8, no. Number 1-2, 2009.

[96] V. M. Loscri and S. G. Marano, "A two-levels hierarchy for low-energy adaptive clustering hierarchy (TL-LEACH)," in *IEEE 62nd Vehicular Technology Conference*, 2005.

[97] W. B. Heinzelman, A. P. Chandrakasan and H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," *IEEE Transaction on Wireless Communications,* vol. 01, no. 04, 2002.

[98] R. A. Akhtar, A. A. Minhas and S. Jabbar, "Energy Aware Intra-Cluster Routing For Wireless Sensor Networks," *International Journal for Hybrid Information Technology,* vol. 13, no. 1, January 2010.

[99] W. Dargie, "Dynamic Power Management in Wireless Sensor Networks: State-of-the-Art," *IEEE Sensors Journal,* vol. 12, no. 5, 2012.

[100] S. Jabbar, "Energy Aware Real-Time Routing in Wireless Sensor Network," Bahria University, Islamabad, 2009.

[101] S. Jabbar, M. Z. Aziz, A. A. Minhas and D. Hussain, "PTAL: Power Tuning Anchors Localization Algorithm For Wireless Ad-Hoc Micro Sensors Network," Bradford, UK, 2010.

[102] Y.-W. Hong and A. Scaglione, "Energy-efficient broadcasting with cooperative transmissions in wireless sensor networks," *IEEE Transactions on Wireless Communications,* vol. 5, no. 10, pp. 2844 - 2855, 2006.

[103] J. Sanchez, P. Ruiz and Marin-Perez, "Beacon-less geographic routing made practical: challenges, design guidelines, and protocols," *IEEE Communications Magazine,* vol. 47, no. 08, p. 85 – 91, 2009.

[104] J. Son and T.-Y. Byun, "A Routing Scheme with Limited Flooding for Wireless Sensor Networks," *International Journal of Future Generation Communication and Networking,* vol. Vol. 3, no. No. 3, September 2010.

[105] S. Subramanian, S. Shakkottai and A. Arapostathis, "Broadcasting in Sensor Networks: The Role of Local Information," in *25th IEEE International Conference on Computer Communications, INFOCOM* , Barcelona, Catalunya, Spain, 2006.

[106] D. Dubhashi, O. Häggström, L. Orecchia, A. Panconesi, C. Petrioli and A. Vitaletti, "Localized Techniques for Broadcasting in Wireless Sensor Networks," *Algorithmica Journal,* vol. 49, no. 4, pp. 412-446, 2007.

[107] J. Wu and W. Lou, "Forward-Node-Set-Based Broadcast in Clustered Mobile Ad Hoc Networks," *Journal of Wireless Communication and Mobile Computing,* vol. 3, no. 2003, p. 155—173, 2003.

[108] M.Murugesan and A.Krishnan, "Efficient Forward Node List Algorithm for Broadcasting in Asymmetric Mobile Ad hoc networks," *International Journal on Computer Science and Engineering,* vol. 02, no. 04, pp. 1219-1222, 2010.

[109] A.Vallimayil, V. Dhulipala, K. Raghunath and R.M.Chandrasekaran, "Role of Relay Node in Wireless Sensor Network: A Survey," in *3rd International Conference on Electronics Computer Technology*, Kanyakumari, 2011.

[110] K. Lee and H. Lee, "A Self-Organized and Smart-Adaptive Clustering and Routing Approach for Wireless Sensor Networks," *International Journal of Distributed Sensor Networks,* p. 13, 2012.

[111] S. Jabbar, A. A. Minhas and R. A. Akhtar, "SPERT: A Stateless Protocol For Energy-Sensitive Real-Time Routing For Wireless Sensor Network," Karachi, Pakistan, 2009.

[112] A. A. Minhas, S. Jabbar, M. Z. Aziz and W. Mahmood, "QERT: Query-Based Energy-Aware Real-Time Routing For Wireless Sensor Network," in *ScalCom'2010*, Bradford, UK, 2010.

[113] M. Qayyum, S. Jabbar, F. Azam and S. Rizwan, "Stagnant Free Ant Based Heuristic Routing In Wireless Sensor Network," in *International Conference on Collaboration Technologies and Systems*, Denver, Colorado, USA, 2012.

[114] G. Oddi, D. Macone, A. Pietrabissa and F. Liberati, "A proactive link-failure resilient routing protocol for MANETs based on reinforcement learning," in *20th Mediterranean Conference on Control & Automation*, 2012.

[115] M. Aissani, S. Bouznad, A. Hariza and S.-E. Allia, "An Effective Approach for Handling both Open and Closed Voids in Wireless Sensor Networks," *Sensors & Transducers Journal,* vol. 14, no. 2, pp. 196-210, March 2012.

[116] M. Aissani, S. Bouznad, S.-E. Allia and A. Hariza, "Efficient Forwarding Approach on Boundaries of Voids in Wireless Sensor Networks," *International Journal on Advances in Telecommunications,* vol. 5, no. 3, 2012.

[117] Q. Fang, J. Gao and L. Guibas, "Locating and bypassing routing holes in sensor networks," *Journal of Mobile Networks and Applications,* vol. 11, no. 2, p. 187–200, October 2006.

[118] T. He, J. A. Stankovic, C. Lu and T. Abdelzaher, "A Spatiotemporal Communication Protocol for Wireless Sensor Networks," *IEEE Transactions on Parallel and Distributed Systems,* vol. 6, no. 10, pp. 995-1006, 2005.

[119] M. C. Taekyoung, S. M. Yong, Y. y. Victor and C. Leung, "Reliable and Energy-Efficient Routing Protocol in Dense Wireless Sensor Networks," *International Journal of Sensor Networks,* vol. 4, no. 1/2, pp. 104-117, July 2008.

[120] B. Bakr, Lilien and Leszek, "LEACH-SM: A protocol for extending wireless sensor network lifetime by management of spare nodes," in *International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, 2011.

[121] S. Jabbar and S. H. Shah, "Optimizing Throughput using Energy Efficient Data Aggregation Technique for Cluster based Wireless Sensor Network," *International Journal of Distributed Sensor Networks (IJDSN),* Marh 2013.

[122] R. Sarkar, X. Zhu and G. Jie, "Spatial Distribution in Routing Table Design for Sensor Networks," in *IEEE INFOCOM*, Rio de Janeiro, 2009.

[123] C.-S. Nam, H.-Y. Cho and D.-R. Shin, "Efficient path setup and recovery in wireless sensor networks by using the routing table," in *2nd International Conference on Education Technology and Computer*, 2010.

[124] V. Katiyar, N. Chand and S. Soni, "A Survey on Clustering Algorithms for Heterogeneous Wireless Sensor Networks," *Int. J. Advanced Networking and Applications,* vol. 2, no. 04, pp. 745-754, 2011.

[125] D. Kumar, T. Aseri and R. Patel, "EECDA: Energy Efficient Clustering and Data Aggregation Protocol for Heterogeneous Wireless Sensor Networks," *Int. J. of Computers, Communications & Control,* vol. 6, no. 01, pp. 113-124, March 2011.

[126] A. Iwata, C.-C. Chiang, G. Pei, M. Gerla and T.-W. Chen, "Scalable routing strategies for ad hoc wireless networks," *IEEE Journal on Selected Areas in Communications,* vol. 17, no. 08, p. 1369 – 1379, 1999.

[127] S. K. Singh, M. P. Singh and D. K. Singh,, "A Survey of Energy-Efficient Hierarchical Cluster-Based Routing in Wireless Sensor Networks," *Int. Journal of Advanced Networking and Applications,* vol. 02, no. 02, pp. 570-580, 2010.

[128] N. M. Khan, K. Zubair and G. Ahmed, "Gradient cost establishment (grace) for an energy-aware routing in wireless sensor networks," *EURASIP Journal on Wireless Communications and Networking,* vol. 2009, p. 15, 2009.

[129] N. Hassan, N. M. Khan, G. Ahmed and R. Ramer, "Real-time gradient Cost Establishment (RT-GRACE) for an energy-aware routing in Wireless Sensor Networks," in *IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing*, Melbourne, VIC, 2013.

[130] S. Naeimi, H. Ghafghazi, C.-O. Chow and H. Ishii, "A Survey on the Taxonomy of Cluster-Based Routing Protocols for Homogeneous Wireless Sensor Networks," *Sensors,* vol. 12, 2012.

[131] M. J. Handy, M. Haase and D. Timmermann, "Low energy adaptive clustering hierarchy with deterministic cluster-head selection," in *4th International Workshop on Mobile and Wireless Communications Network*, 2002.

[132] M. Diwakar and S. Kumar, "An Energy Efficient Level Based Clustering Routing Protocol For Wireless Sensor," *International Journal Of Advanced Smart Sensor Network Systems, (IJASSN),* vol. 02, no. 02, 2012.

[133] Asaduzzaman and H. Y. Kong, "Energy efficient cooperative LEACH protocol for wireless sensor networks," *Journal of Communications and Networks,* vol. 12, no. 04, p. 358 – 365, 2010.

[134] M. Ye, C. Li, G. Chen and J. Wu, "An Energy Efficient Clustering Scheme in Wireless Sensor Networks," *Adhoc & Sensor Wireless Networks Journal,* vol. 03, pp. 99-119, 2007.

[135] T. Murata and H. Ishibuchi, "Performance Evaluation of Genetic Algorithms for Flowshop Scheduling Problems," in *1st IEEE conf. Evolutionary Computation*, Orlando, FL, 1994.

[136] H. M. Ammari and S. K. Das, "Centralized and Clustered k-Coverage Protocols for Wireless Sensor Networks," *IEEE Transactions on Computers,* vol. 61, no. 1, pp. 118-133, 2012.

[137] P.-T. Yang and S. Lee, "A Distributed Reclustering Hierarchy Routing Protocol Using SocialWelfare in Wireless Sensor Networks," *International Journal of Distributed Sensor Networks,* vol. 2012, p. 14, 2012.

[138] J. Yu, Y. Qi, G. Wang, Q. Guo and X. Gu, "An Energy-Aware Distributed Unequal Clustering Protocol for Wireless Sensor Networks," *International Journal of Distributed Sensor Networks,* vol. 2011, 2011.

[139] C. Li, M. Ye, G. Chen and J. Wu, "An Energy-Efficient Unequal Clustering Mechanism for Wireless Sensor Networks," in *IEEE International Conference on Mobile Adhoc and Sensor Systems Conference, 2005.* , Washington, DC, 2005.

[140] M. Sharma and KalpanaSharma, "An Energy Efficient Extended LEACH (EEE LEACH)," in *International Conference on Communication Systems and Network Technologies*, Washington, DC, USA, 2012.

[141] C. Lombriser, U. Hunkeler and H. L. Truong, "Centrally controlled clustered wireless sensor networks," IBM Research Report, 2011.

[142] Z. Yu, Y. Liu and Y. Cai, "Design of an Energy-Efficient Distributed Multi-level Clustering Algorithm for Wireless Sensor Networks," in *4th International Conference on Wireless Communications, Networking and Mobile Computing*, Dalian, 2008.

[143] M. Aslam, T. Shah, N. Javaid, A. Rahim, Z. Rahman and Z. A. Khan, "CEEC: Centralized energy efficient clustering a new routing protocol for WSNs," in

Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), 2012 9th Annual IEEE Communications Society, Seoul, June 2012.

[144] G. Chen, C. Li, M. Ye and JieWu, "An unequal cluster-based routing protocol in wireless sensor networks," *Wireless Networks,* vol. 15, p. 193–207, 2007.

[145] O. Younis and S. Fahmy, "Distributed clustering in ad-hoc sensor networks: a hybrid, energy-efficient approach," *IEEE Transactions on Mobile Computing,* vol. 03, no. 04, 2004.

[146] H. Chan and A. Perrig, "ACE: An Emergent Algorithm for Highly Uniform Cluster Formation," in *First European Workshop on Sensor Networks*, Berlin Heidelberg, 2004.

[147] K. Majumder, "Clustered Chain based Power Aware Routing (CCPAR) Scheme for Wireless Sensor Networks," *International Journal on Computer Science and Engineering,* vol. 02, no. 09, pp. 2953-2963, 2010.

[148] D. J. Baker and A. Ephremides, "The Architectural Organization of a Mobile Radio Network via a Distributed Algorithm," *IEEE Trans. Commun.,* vol. 29, no. 11, p. 694–701, 1981.

[149] D. Wang., "Power-Mitigating Scheme for Clusterheads in Wireless Sensor Networks," *Adhoc & Sensor Wireless Networks Journal,* vol. 09, pp. 239-253, 2010.

[150] M. Qin and R. Zimmermann, "An energy-efficient voting-based clustering algorithm for sensor networks," in *Sixth International Conference on Software Engineering*, Seoul, 2005.

[151] D. Wei, Y. Jin, S. Vural, K. Moessner and R. Tafazolli, "An Energy-Efficient Clustering Solution for Wireless Sensor Networks," *IEEE transactions on wireless communications,* vol. 10, no. 11, November 2011.

[152] T. Shu, M. Krunz and S. Vrudhula, "Power balanced coverage-time optimization for clustered wireless sensor networks," in *The ACM International Symposium on Mobile Ad Hoc Networking and Computing*, New York, NY, USA, 2005.

[153] S. Amritha, T. C and S. Thampi, "An ACO Algorithm for Effective Cluster Head Selection," *Journal of Advances in Information Technology,* vol. 2, no. 1, p. 50, 2011.

[154] Y. Wang and B. Ramamurthy, "Layered Clustering Communication Protocol for Wireless Sensor Networks," in *CSE Conference and Workshop Papers*, 2007.

[155] S. K. Singh, M. P. Singh and D. K. Singh, "A Survey of Energy-Efficient Hierarchical Cluster-Based Routing in Wireless Sensor Networks," *Int. Journal of Advanced Networking and Applications,* vol. 02, no. 02, pp. 570-580, 2010.

[156] B. A. Said, E. abdellah, A. B. Hssane and M. L. Hasnaoui, "Improved and Balanced LEACH for heterogeneous wireless sensor networks," *International Journal on Computer Science and Engineering,* vol. 02, no. 08, pp. 2633-2640, 2010.

[157] M. Yu, K. Leung K. and A. Malvankar, "A Dynamic Clustering and Energy Efficient Routing Technique for Sensor Networks," *IEEE Transactions On Wireless Communications,* vol. 06, no. 08, 2007.

[158] H. Jan, A. Paul, A. A. Minhas, A. Ahmad, S. Jabbar and M. Kim, "Analysis of Intra Cluster Routing Techniques in Wireless Sensor Networks," *Peer to Peer networking and Applications, Special Issue, Cloud, Grid, P2P and Internet Computing: Recent Trends and Future Directions,* p. 13, 2014.

[159] M. Maimour, H. Zeghilet and F. Lepage., Cluster-based Routing Protocols for Energy Efficiency in Wireless Sensor Networks, Y. K. Tan, Ed., Intechopen, 2010.

[160] A. Forster and A. L. Murphy, "CLIQUE: Role-free clustering with Q-learning for wireless sensor networks," in *29th IEEE International Conference on Distributed Computing Systems*, Washington, DC, USA, 2009.

[161] H. Zeghilet, N. Badache and M. Maimour, "Energy efficient cluster-based routing in wireless sensor networks," in *IEEE Symposium on Computers and Communications*, Sousse, Tunisia, 2009.

[162] S. Jabbar, A. A. Minhas, T. Rahseed and S. Rho, "Heuristic Approach for Stagnation Free Energy Aware Routing in Wireless Sensor Network," *Ad Hoc Sensor Wireless Network (AHSWN),* vol. 0, pp. 1-25, December 2014.

[163] S. Jabbar, R. Iram, A. A. Minhas, I. Shafi, S. Khalid and M. Ahmad, "Intelligent Optimization Of Energy Aware Routing In Wireless Sensor Network Through Bio-

Inspired Computing: Survey And Future Directions," *International Journal of Distributed Sensor Networks,* vol. 2013, p. 13, 2013.

[164] D. Takaishi, H. Nishiyama, N. Kato and R. Miura, "Towards Energy Efficient Big Data Gathering in Densely Distributed Sensor Networks," *IEEE Transactions on Emerging Topics in Computing,* vol. 2, no. 3, pp. 388-397, September 2014.