STUDIES ON THE ENERGY EFFICIENT TECHNIQUES FOR WIRELESS SENSOR NETWORKS

THESIS

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CERTIFICATE

Certified that this thesis entitled **“STUDIES ON THE ENERGY EFFICIENT TECHNIQUES FOR WIRELESS SENSOR NETWORKS”** submitted for the award of the degree of **DOCTOR OF PHILOSOPHY** in ELECTRONICS AND COMMUNICATION ENGINEERING of the Pondicherry University, Pondicherry is a record of original research work done by **Mrs. J.VIDHYA** during the period of study under my supervision and that the thesis has not previously formed the basis for the award to the candidate of any Degree, Diploma, Associateship, Fellowship or other similar titles. This thesis represents independent work on the part of the candidate.

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ABSTRACT

The rapid advancement of radio technologies in the 70's stimulated the development of mobile communication systems that would meet the needs of young professionals on the move. Hundreds of millions of people exchange information every day using laptops, Personal Digital Assistant (PDA), pagers, cellular phones and other wireless communication devices. At present, wireless mobile networks and devices are becoming increasingly popular than ever before. Users demand for the access to information and communication anywhere and anytime. To afford seamless connectivity it is necessary that wireless devices communicate among themselves without routers, base stations or service providers. This has led to the progression of adhoc networks (infrastructureless networks). Although adhoc networks were used to setup communication for specialised, customised and extemporaneous applications during large scale natural calamities or military operations, the nodes in the network are not engrossed to observe the physical happening.

Researchers realised the need to develop a wireless sensor technology to sense the physical phenomenon when nodes are deployed in a hostile environment. The development of this technology has been fuelled by advances in electronic miniaturisation, wireless communication, low cost, low power and multifunctional sensors. Sensor network is characterised by multiple nodes that sense, collect and disseminate information about the real world through wireless medium. Senor nodes are severely constrained by the amount of battery power available and are left unattended after deployment, thus limiting the lifetime and quality of the network. This concept of non-renewable or disposable nodes has pushed energy consideration to the forefront of sensor network research.

When a sensor node routes the data from sensing field directly to the sink or destination, the node consumes larger energy due to fading, interference environment and radio irregularity. To achieve high energy efficiency clustering technique has gained significant interest for large scale wireless sensor network. In

this approach each cluster has a single head node and multiple non-cluster head nodes to route the data to destination. The non-cluster head nodes transmit the data to the head node. The head node inturn transmits the data to the sink. Sensor nodes share the common radio channel for communication. Managing the radio channel for reliable information transfer without collision under extreme traffic conditions in intra and inter-cluster communication from energy efficient perspective is essential. Therefore, the lifetime of Wireless Sensor Network (WSN) primarily relies on the Medium Access Control (MAC) protocol, as it controls the switching of the radio of the sensor nodes. Reducing the power consumed by the sensor nodes can be accomplished by selecting the suitable MAC scheme depending on the contention level of the network.

The throughput of the WSN however reduces due to the fading effects and interference of wireless medium. This is generally mitigated through spatial diversity techniques. Spatial diversity employs multiple cooperative nodes at the transmitter and receiver and is very promising, since it does not increase the transmit power and signal bandwidth. This can be efficiently exploited through Multi Input Multi Output (MIMO) systems, i.e., system with multiple transmitting and multiple receiving cooperative nodes. This dissertation deals with the study of energy efficient MAC, MIMO and routing protocol based on clustering approach to enhance the lifetime of WSNs.

A hybrid MAC protocol is proposed using Bit Map Assisted (BMA) MAC and nanoMAC protocol for intra and inter-cluster communication respectively to minimise energy and delay for the cluster based sensor network. To combat fading and radio interference of wireless medium MIMO MAC scheme is realised by the selection of fixed cooperative sending and receiving group sizes with two, three and four cooperative nodes. To reduce the retransmission probability and energy consumption of sensor nodes, Space Time Coding (STC) techniques such as Space Time Block Code (STBC) and Space Time Trellis Code (STTC) are incorporated for the MIMO MAC scheme. STC scheme provides diversity gain and seems effective in improving the network performance.

Moreover, to ensure the stability of transmission queues at the nodes, a threshold based MAC protocol for cooperative MIMO transmission using STC is propounded. The protocol dynamically selects the cooperative group size that has minimum energy and delay subject to the cooperative threshold taking into account the neighbouring network traffic. Furthermore, to route the data from the source cluster to destination and also combat fading, cooperative MIMO routing schemes such as Cooperative Low Energy Adaptive Clustering Hierarchy (C-LEACH) and Cluster Head Cooperative Low Energy Adaptive Clustering Hierarchy (CH-C-LEACH) are proposed by extending the MIMO technique to conventional LEACH protocol.

To summarise, in this work an efficient MAC, MIMO and routing scheme for WSN based on clustering approach has been evaluated. The proposed approach is found to be energy efficient, offers lesser transmission delay and enhances the network lifetime. The related further study is to implement error control code combining technique along with the best modulation and transmission strategy to extend the lifetime of sensor network.

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LIST OF ABBREVIATIONS

ACK	Acknowledgement
AWGN	Additive White Gaussian Noise
BCDCP	Base station Controlled Dynamic Clustering Protocol
BER	Bit Error Rate
BMA	Bit Map Assisted
CFO	Carrier Frequency Offset
CH	Cluster Head
CH-C-LEACH	Cluster Head Cooperative LEACH
C-LEACH	Cooperative LEACH
CMST-DC	Cluster based Minimal Spanning Tree with Degree Constrained
CN	Cooperative Node
Cooperate-REQ	Cooperative Request
CS	Carrier Sense
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CW	Collision Window
DSP	Digital Signal Processing
E-TDMA	Energy-efficient TDMA
GHz	Giga Hertz
H-Sensor	High-end Sensor
HSN	Heterogeneous Sensor Network
ID	Identifier
IEEE	Institution of Electrical and Electronics Engineers
Join-REQ	Join Request
KHz	Kilo Hertz

LEACH	Low Energy Adaptive Clustering Hierarchy
LEACH-C	LEACH Centralised
L-Sensor	Low-end Sensor
MAC	Medium Access Control
MACA	Medium Access with Collision Avoidance
MANET	Mobile Adhoc Network
Mbps	Mega bits per second
MCTS	MIMO CTS
MHz	Mega Hertz
MIMO	Multi Input Multi Output
MISO	Multi Input Single Output
MIT	Massachusetts Institute of Technology
MMSE	Minimum Mean Square Estimator
MRTS	MIMO RTS
NCTS	Negative CTS
np-CSMA	Non-persistent CSMA
PDA	Personal Digital Assistant
PEGASIS	Power Efficient GAthering in Sensor Information Systems
PER	Packet Error Rate
PTDMA	Probabilistic TDMA
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
REECR	Residual Energy and Energy Consumption Rate
RF	Radio Frequency
RRCH	Round Robin Cluster Head
RRTS	Recruiting RTS
RSS	Received Signal Strength
RTS	Request To Send
SCTS	Sequential CTS
SEP	Stable Election Protocol
SER	Symbol Error Rate

SISO	Single Input Single Output
SMAC	Sensor MAC
SNR	Signal to Noise Ratio
SPEAR	Sensor Protocol for Energy Aware Routing
SPIN	Sensor Protocol for Information via Negotiation
STBC	Space Time Block Code
STC	Space Time Coding
STTC	Space Time Trellis Code
TCH	Target Cluster Head
TCM	Trellis Coded Modulation
TDMA	Time Division Multiple Access
T-MAC	Timeout MAC
VAP	Virtual Area Partition
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network
ZMAC	Zebra MAC

LIST OF SYMBOLS

μ	Energy model transitions from state idle
θ	Energy model transitions from state reply
ρ	Traffic intensity or normalised traffic offered to the channel
ξ	Positive integer
$\in_t(i)$	Permutation of symbols from first column to the t^{th} column in row position, x_i
α	Efficiency of radio frequency power amplifier
λ	Wavelength of transmission
σ^2	Power spectral density of additive white Gaussian noise channel
$\varphi(i)$	Threshold for possible choice of cluster sizes
$[.]^*$	Complex conjugate operation
$[.]^T$	Transpose operation
a	Constant
agg	Aggregation factor
B	Bandwidth
c^k	k^{th} input sequence fed to the STTC encoder
d	Distance between source and destination node
τ_d	Average packet delay
E(A)	Energy consumption on each visit by the node to attempt state
E_{ack}	Energy consumed in sending ACK
E_{arrive}	Energy consumption when reaching the arrive state
E(B)	Energy consumption on each visit by the node to backoff state
E_{br}	Energy spent by destination node to send the notification message
E_{bs}	Energy spent by the source node to send the data
$E_{bs}(k_c)$	Energy spent by the source node to transmit data to cluster head node
$E_{bc0}(k_c,n_T)$	Energy per bit consumed by cluster head node to transmit aggregated data
E_{ch}	Energy consumed by a cluster head node during a single session
E_{col}	Energy consumed by data collection in the third phase
$E_{c0}(k_c, n_T)$	Energy consumed by cluster head node to transmit aggregated data

$E_{cr}(k_c, n_R)$	Energy consumed by n_R receiving cooperative nodes
$E_{cs}(k_c, n_T)$	Energy consumed by n_T cooperative sending nodes to transmit data
E_{cts}	Energy consumed in sending CTS packet
E_{data}	Energy consumption for data transmission
$E(I)$	Energy incurred in each visit of node to idle state
E_{in}	Energy consumed by a non-source node during a single session
$E(k_c, n_T)$	Over all energy consumption for each round of data transmission
E_M	Total energy consumption for one hop MIMO transmission
E_{mcts}	Energy consumed in sending MIMO CTS
E_{mrts}	Energy consumed in sending MIMO RTS
$E_{recruit}$	Energy consumed on recruiting neighbouring nodes
E_{rec_d}	Energy required for recruiting destination
E_{rec_s}	Energy required for recruiting source
E_{round}	Total system energy dissipated during each round
E_{rts}	Energy consumed in sending RTS
E_{rrts}	Energy consumed in sending RRTS
$E_r(k_c)$	Energy consumed by the H-sensor node
E_{RX}	Average receiver energy consumption
E_{scts}	Energy consumed in sending SCTS
E_{si}	Energy consumed in a cluster during the i^{th} session
E_{sn}	Energy consumed by a source node during a single session
$E_{success}$	Energy consumption upon reaching the success state from the attempt state
$E_s(k_c)$	Energy consumed by a cluster member to transmit data to cluster head
E_{TX}	Average transmitter energy consumption
Es_{coop}	Energy consumption for a successful transmission attempt
Eu_{coop}	Energy consumption for an unsuccessful transmission attempt
E_{wait}	Energy spent waiting for transmission
F	Block size of the STBC code
F_n	Number of symbols in a frame
g^m	Multiplication coefficient set sequence

$g_{j,i}^{k}$	Elements of QPSK constellation set
G_1	Gain factor
G_r	Gain of receiving antenna
G_t	Gain of transmitting antenna
h	Fading attenuation coefficient
I_{n_T}	n_T x n_T identity matrix
k	Number of sessions in a round
K	Unique packet error probability for possible cluster choices
k_c	Number of clusters
L	Frame length in bits
M	Network diameter
M_1	Link margin
M_{RX}	Receiver power consumption
M_{Slp}	Sleep power consumption of transceiver
M_{TX}	Transmitter power consumption
n	Path loss factor
n_i	Number of source nodes in i^{th} session/frame
n_k	Average number of hops
n_R	Number of receiving cooperative nodes
n_T	Number of transmit cooperative nodes
N	Number of sensor nodes
N_f	Receiver noise figure
N_0	Noise power spectral density
T_{bc}	Time periods for transmission of one block of coded symbols
p_e	Bit error probability
$p_e(n_T,n_R)$	Probability of error for each possible choice of n_T, n_R
p_p	Packet error probability
p	Transmit probability of each node
p_b	Probability of finding channel busy during carrier sense
P_{cr}	Circuit power consumption of the receiver
P_{ct}	Circuit power consumption of the transmitter
p_{ers}	Non-persistence probability of nanoMAC

P_i	Power consumption during the idle mode
$p_{prob\{1,2,3\}}$	Probabilities related to arriving to a certain state
P_r	Power consumption during the reception
p_s	Probabilities of no collision during RTS transmission
p_{senh}	Probabilities of no collision during CTS transmission
P_t	Power consumption during the transmission
Q	Queue length
R	Transmission rate
R_{bt}	Number of times for exchanging and updating routing table for each round
R_{ts}	Routing table size
r_t^j	Received signal at cooperative node j at time t
s	Packet size
S	Channel throughput
$sgn_t(i)$	Sign of x_i in the t^{th} column
$S_1(k_c)$	Total number of bits transmitted to cluster head in each round
$S_2(k_c)$	Amount of data after aggregation for each round by H-sensor node
$S_e(k_c,n_T)$	Amount of data required to transmit the $S_2(k_c)$ bits with n_T cooperative nodes
T_{ack}	Transmission time for the ACK
T_b	Bit duration
T_{bb}	Incremented backoff time
T_{bp}	Un-incremented backoff time
T_{Br}	Transmission time of a recruitment message sent by the destination node
T_{Bs}	Transmission time required for the source node to send the data packet
T_c	Time required to transmit /receive a control packet
T_{ch}	Time required for cluster head to transmit a control packet
T_{col}	Time required by the cooperating receiving nodes to send the data
T_{cp}	Normalised time for transmission of control packets
T_{CS}	Time required for carrier sensing

T_{cts}	Transmission time for the CTS
T_d	Time required to transmit /receive a data packet
T_{data}	Transmission time for the data
T_f	Frame transmission time interval
T_p	Normalised propagation time
T_{pr}	Time required to transmit a preamble
T_r	Random delay
T_{rts}	Transmission time for the RTS
T_{wait}	Duration for which sender waits for an ACK
Ts_{coop}	Duration of transmission attempt that is successful
Tu_{coop}	Duration of transmission attempt that is unsuccessful
ν_k	Memory order of the kth shift register
x_i	Transmitted sequence from i^{th} cooperative node
$\overline{x}_i$	Decision statistics obtained at the decoder
x_j	Transmitted sequence from j^{th} cooperative node
x_k	k modulated signals
$x_k{}^*$	Conjugate of k modulated signals
x_t^i	Encoder output at time t for transmit cooperative node i
Y	STBC transmission matrix
Y^*	Complex STBC transmission matrix
Y^H	Hermitian of Y
Y_t	Branch metric computed at receiver

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The fast emerging trends in wireless industry are influencing our lifestyles, driving businesses and synergistically thriving with research efforts. Recent manifestations of affordable, portable wireless communication and computation devices and concomitant advances in the communication infrastructure have tremendously increased the demands for ubiquitous wireless access. This has led to the exponential growth of the cellular network, which is based on the amalgamation of wired and wireless technology.

Infrastructure wireless network connectivity is getting deployed in every conceivable place: homes, offices, public libraries, cafes and university campuses. Recently, Wireless Local Area Network (WLAN) commodities have prevailed alongside the cellular infrastructure as the primary wireless coverage source. More and more new products for WLANs are presented every day. Also, a large number of Personal Digital Assistant (PDA) and mobile phones have access to wireless technology. The prologue of inexpensive WLAN routers allowed many households to install internet access points. Further, it is worth noting that the general tendency of converging between WLAN and cellular network is accelerating [1]. The number of cellular network and internet users have increased significantly and are fast approaching two billion worldwide.

The research and development devoted to traditional wireless networks has increased worldwide significantly for enabling wireless communication between users with fixed infrastructure. The growth of scientific community in the realm of telecommunications has shifted recently to have communication between users without fixed infrastructure.

The infrastructure cellular network [1] has fixed and wired gateways or fixed base stations which are connected to other base stations through wired backbone. Each node is within the range of a base station. When a mobile host travels out of range of one base station and into the range of another, handoff occurs to continue communication seamlessly throughout the network. The major tribulation is the difficulty in handoff smoothly from one base station to another base station without noticeable delay or packet loss. Another problem is that networks based on the cellular structure are limited to places having cellular network infrastructure.

The infrastructureless networks have no fixed routers, every node in the network serve as a router. Such networks are required during large scale natural calamities or during military operations where fixed infrastructure is intricate to construct. Wireless adhoc networks are infrastructureless networks that do not rely on the pre-established infrastructure [2,3]. The communication in this network is fully decentralised and self organising in nature. There is no central entity or base station controlling or regulating the network traffic. At the same time, the network should provide scalability in number of users. This form of network is limited in transmission range and is typically smaller compared to the range of cellular systems.

Subsequently, the Mobile Adhoc Networks (MANETs) have been developed to support scalability and to guarantee the network performance [4]. The nodes in mobile adhoc network intercommunicate via single hop and multihop path in a peer-to-peer fashion. Energy consumption is not of prime importance in MANETs as its energy sources have high capacity and can be rejuvenated and replaced. When nodes are deployed in a hostile environment to sense a physical phenomenon, it is highly important for small sensing devices to scrimp and save the energy consumption of nodes. This paves the way to another type of application for the wireless connectivity, the sensor networks.

Due to recent advances in wireless communication and micro electronics over the last few years, the development of networks of low cost, low power and multifunctional sensors have received increasing attention. Indeed, technical review at Massachusetts Institute of Technology (MIT) and Global Future identify wireless sensor networks as one of the “10 emerging technologies that will change the world”. Wireless Sensor Network (WSN) supports wide range of potential applications such as environmental monitoring, surveillance, military, health and security [5-7].

1.1.1 Wireless Sensor Network Model

A wireless sensor network is composed of large number of sensor nodes that are densely deployed inside the physical phenomenon with limited storage and radio capabilities [8-11]. The scattered sensor nodes in the sensor field sense the information and send the data to sink (processing centre). The data from the sink node is reported to user through internet and satellite (Fig.1.1).

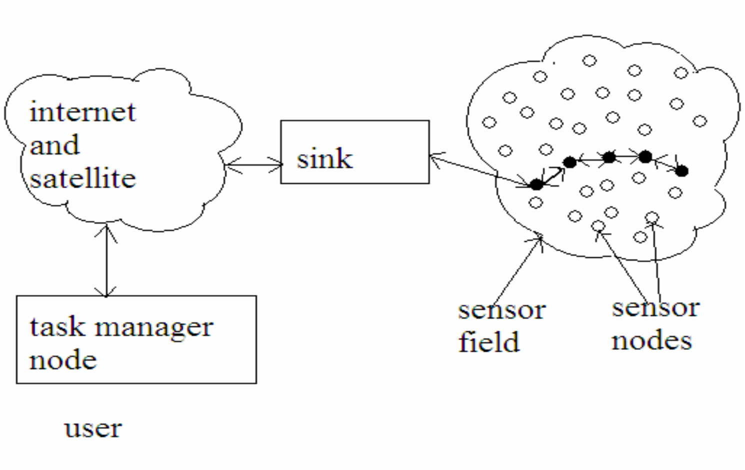

Fig.1.1 Basic network model

According to the distance of sensor nodes to the sink, WSNs can be classified as single hop or multihop systems [12]. In single hop WSN, all sensor nodes transmit the data directly to the sink, while in a multihop WSNs, some nodes can deliver their data to the sink via intermediate nodes. Single hop networks have much simpler structure and control, and fit into the applications of small sensing areas. Nodes farther away from the sink tend to die faster due to drainage of energy. Multihop networks promise wider applications at the cost of higher complexity. Nodes nearer to the sink tend to die faster as they route most of the data to destination.

1.1.2 Cluster Based Model

Clustering is the most promising technique that can significantly save the energy of sensor nodes and improve the scalability of the network [13]. In clustering approach, sensors group together to form clusters. One of the sensors in each of the cluster will be elected as cluster head. The elected cluster head will be responsible for relaying data from each sensor in the cluster to the remote receiver. In addition, data fusion and data compression can occur in the cluster head by considering the potential correlation among data from neighbouring sensors. The energy and delay consumed by cluster head depends on its distance to sink. The cluster heads normally use single hop or multihop communication with the sink based on the application to conserve energy.

Clustered sensor networks can be classified into two broad types such as homogeneous and heterogeneous sensor networks. In homogeneous sensor network [14-16], all the sensor nodes are identical in terms of energy and hardware complexity. This type of network consists of purely static clustering i.e., cluster heads once elected, serve for the entire lifetime of the network. It is evident that the cluster head nodes will be overloaded with the long range transmissions to the remote sink. Also, the extra processing is necessary for the cluster head for data aggregation and protocol coordination. As a result, the cluster head nodes expire before other nodes. It is desirable to ensure that all the nodes run out of their battery at about the same time to maximise the network lifetime.

One way to ensure balanced energy consumption is to rotate the role of a cluster head uniformly among all the nodes. This dynamic clustering approach brings extra overhead and consumes high amount of energy during the set-up process of the cluster and election of cluster head. To reduce the set-up communication overhead, heterogeneous sensor network [17] is formed by deploying a small number of High-end sensors (H-sensors) and large number of Low-end sensors (L-sensors). Clusters are formed in the network around each H-sensor, which serve as cluster heads. The H-sensors have more energy supply, longer transmission range and high data rate than L-sensors. The L-sensor does basic sensing as well as relaying of packets within each cluster. The H-sensor conducts data fusion within each cluster, and transmits the aggregated data to the sink node. Hence, heterogeneous clustering technique has gained more importance for energy conservation in wireless sensor network.

1.2 NEED FOR ENERGY EFFICIENCY

In all wireless networks, nodes must share a single medium for communication. Network performance largely depends upon how efficiently and fairly the nodes can share this common medium. The packet transmission of the nodes is directly handled by the Medium Access Control (MAC) layer. Moreover, a significant portion of the node’s energy is spent on packet transmission and listening to the medium for anticipated packet reception.

In the context of WSNs, designing an efficient MAC [18] protocol is extremely critical. The nodes of a WSN carry extremely low energy resources and are mostly unattended after deployment. The node lifetime of WSN entirely depends on how energy can be conserved during communication. Once the battery of the nodes are exhausted, the nodes are abandoned. Therefore, it is very essential to use the power of the battery efficiently to improve the longivity of the sensor network.

Although, some exhausted nodes could be compensated using redundant neighbouring nodes, certain situations may arise rendering a part of the network completely inactive due to low connectivity and insufficient coverage or making that part of the network inaccessible as well as isolated from the other parts. Such scenarios could be averted by avoiding unnecessary transmissions and having longer listen periods for nodes activities that consume the highest amount of power in nodes.

Another related issue is the high node density in WSNs. Although, the transmission ranges are lower, a fairly high number of nodes can contend for the medium, atleast in certain portions of the network. By the token, transmissions from each node would increase the background noise and may disrupt their own receptions. Thus, the MAC schemes for WSN should be carefully designed to achieve the optimum performance toward the intended application.

A MAC protocol decides competing nodes when to access the shared medium (the radio channel) and tries to ensure that no two nodes are interfering with each other's transmissions. In the unfortunate event of a collision, a MAC protocol may deal with it through some contention resolution or scheduling algorithm by resending the message later at a randomly selected time such as Carrier Sense Multiple Access (CSMA) or accessing the channel in a specific schedule such as time division multiple access, frequency division multiple access or code division multiple access to minimise the energy and delay in data transmission [19-22].

Unlike wired channels, which are static and predictable, wireless channels are subjected to time varying impairements such as noise, interference and fading. A proven way to mitigate these effects is by employing diversity techniques. Current diversity techniques include space (antenna) diversity, frequency diversity and time diversity. Space diversity uses two or more physically separated antennas to create multiple independent fading channels. Frequency diversity takes advantage of the fact that different carrier frequencies, sufficiently spaced out, will undergo different fading characteristics over a channel. In time diversity, signals representing the same information are sent over the channel at different times under different fading conditions.

Recent breakthroughs in Digital Signal Processing (DSP) have allowed wireless communication systems to utilise both space and time diversity to address system performance needs by employing multiple antennas at transmitter and receiver to create a system with independently fading channels. A system employing more than one transmitting and receiving antenna is called Multi Input Multi Output (MIMO) system. MIMO systems have been shown to reduce the retransmission probability and lower transmission energy than that of Single Input Single Output (SISO) systems [23,24].

MIMO can be easily realised through Space Time Coding (STC) which transmits multiple copies of data stream across number of antennas [25-27]. The design of these codes takes into account a trade-off between decoder complexity at receiver, maximising the information rate and minimising decoding errors. Copies of the signal received through multiple antennas are combined in an optimal way to extract information from each of them. This ensures optimal reception of data in a potentially difficult environment with noise, interference and fading associated with wireless scenario.

The transmission delay and energy are of prime importance in the process of evolution of wireless communication systems. To ensure reliable communication over the radio channel, a system must overcome fading and interference. However, in WSNs incorporating MIMO MAC directly is impractical as the node is usually limited in size and it is infeasible to mount multiple antennas in each device. Fortunately, if multiple nodes collaborate or cooperate, a virtual antenna array can be formed to achieve spatial diversity, even though each node has only one antenna in WSN. Moreover, if 8 nodes near the sender and receiver cooperate to form sending and receiving group, the amount channel estimation at the receiver in WSN can be reduced from 64 to 8. In addition, the clustered architecture can simplify network management and routing with large number of sensor nodes. This can greatly reduce the energy consumption and transmission delay of sensor nodes without compromising the quality of the network.

1.3 SCOPE OF THE WORK

The present wireless communication networks require high energy efficiency with lesser transmission delay to maximise the system lifetime. Sensor networks have their limitations on energy and packet transmission delay due to interference, radio irregularity and fading. The search to fulfill this requirement is to consider an efficient MAC, routing and MIMO schemes to enhance the system performance using a cluster based architecture in a hostile environment.

Initially, TDMA and Energy efficient TDMA (E-TDMA) MAC schemes were employed for intra-cluster communication and Medium Access with Collision Avoidance (MACA) and non-persistent Carrier Sense Multiple Access (np-CSMA) MAC schemes for inter-cluster communication for performance improvement in WSN. E-TDMA technique outperformed TDMA and np-CSMA outperformed MACA in terms of energy and delay. However, its key source of energy wastage resulted in collisions, overhearing, control packet overhead and idle listening to the wireless medium for packet transmission.

Subsequently, MIMO MAC schemes have been used to coordinate the actions of distributed sensors to combat fading and radio channel interference of wireless medium. The MIMO is realised virtually with the cooperative sending and receiving groups. Diversity gain is achieved through various types of space time codes to reduce channel fading, interference to improve the performance of wireless communication systems.

Furthermore, attempts have been made to increase the network lifetime incorporating multihop cooperative Multi Input Single Output (MISO) in Low Energy Adaptive Clustering Hierarchy (LEACH) routing protocol in order to improve the energy efficiency and reliability by balancing the communication load of the network. STC have been proved to be effective in overcoming fading to improve the network performance.

However, to avoid the energy wastage and to maintain a good low latency performance due to idle listening and collisions, an efficient MAC protocol for inter-cluster communication was not suggested for sensor networks to improve the performance. Also, space time codes are not yet explored for enhancing the performance of MIMO MAC scheme. Furthermore, to dynamically select the cooperative group size, an efficient MAC protocol with threshold scheme using site diversity techniques for handling the traffic in WSN has not been explored. Moreover, multihop MIMO STC routing protocol employing cooperative sending and receiving nodes and the use of cluster head as cooperative nodes are not fully exploited with WSNs.

Hence, in the present work, an attempt has been made to improve the lifetime of WSNs. The energy expended and transmission delay is reduced significantly in WSNs with an efficient design of MAC protocol and clustere based routing approach among sensor nodes using cooperative STC schemes.

1.4 OBJECTIVE OF THE WORK

An attempt has been made in the present work to enhance the network lifetime of WSN through cluster based approach by using efficient routing, MAC and MIMO techniques.

The objectives set in the present work are as follows:

- To assess the performance of sensor network using a hybrid MAC protocol in terms of energy and delay by employing Bit Map Assisted (BMA) MAC and nanoMAC protocol for the intra and inter-cluster communication respectively.
- To examine the performance of the MAC system using MIMO scheme utilising STC techniques to accomplish energy savings and minimise delay by allowing sensor nodes to transmit and receive information cooperatively.

- To investigate the performance of cooperative MIMO MAC protocol using a threshold scheme that dynamically updates the cooperative group size based on the queue length at the sending node in achieving energy efficiency and lesser packet delay.

- To evaluate the performance of the LEACH routing protocol using cooperative MIMO scheme to balance the communication load among clusters and prolong the lifetime of sensor nodes.

1.5 ORGANISATION OF THE THESIS

The current chapter provides an overview on WSN system. The need, scope, the principal objectives pertaining to the present work and the organisation of the thesis are presented in this chapter.

Extensive literature associated to the energy management approaches for efficient routing, MAC and MIMO schemes for WSN system has been critically reviewed and presented in Chapter 2. Summary of the review of literature is also furnished.

Chapter 3 narrates an energy efficient hybrid MAC protocol model for both inter-cluster and intra-cluster commumication in WSN. Also, the energy model for the proposed system is devised mathematically and presented sequentially. A detailed discussion on the energy savings with the aid of simulation results for the system employing nanoMAC and BMA MAC protocol are also incorporated in this chapter.

Cooperative MIMO system model for the MAC protocol using STC is described in Chapter 4. The mathematical model to evaluate the performance of the system is cogently presented. Further, the simulation results in terms of energy and delay analysis of both STC scheme and without coding scheme are presented for different diversity orders.

Chapter 5 deals with a threshold scheme for the cooperative MIMO MAC protocol to ensure network stability with the presence of neighbouring traffic. Also a detailed mathematical model for the propounded scheme is presented in this chapter. Finally, a detailed discussion on the simulation results and the performance is succinctly offered for the system with energy and delay employing threshold policy and without cooperative threshold are also incorporated.

Chapter 6 presents the cooperative MIMO routing schemes such as Cooperative LEACH (C-LEACH) and Cluster Head Cooperative LEACH (CH-C-LEACH) extending the conventional LEACH protocol. Also the mathematical model representing the proposed system is devised and presented. Using this approch the energy efficiency to maximise the network lifetime is studied and quantified with results.

Chapter 7 concludes the thesis by emphasizing the major implication of the study. A summary of research contribution and the scope for the future studies are also furnished in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

An exhaustive literature associated with the energy management in WSN for clustering approach was collected and critically analysed in this chapter. A comprehensive review of literature on evolution of the MAC, MIMO and routing schemes to maximise the lifetime of sensor network are also presented. Further, the summary of the review of literature is furnished at the end of the review to justify the scope of present work.

2.2 REVIEW OF LITERATURE

Right from the inception of WSNs, there has been a prime thought to improve its energy consumption and guarantee the packet delay to maximise the lifetime of sensor nodes. F. Akyildiz *et al*. [28] studied exhaustively on WSNs to improve the lifetime and suggested the protocols, and algorithms for sensor network applications. Sensor networks serve many diverse applications from low data rate event driven monitoring to high data rate real time industrial applications.

H. Balakrishnan [29] reported that some high data rate applications can reach sensing rates of 1 kHz to 1 MHz and consume from 10 to 100 Mbps aggregate bandwidth that require five times improvement in channel utilisation. In WSNs, controlling access to channel (generally known as MAC) plays a key role in determining channel utilisation, network delays and power consumption. Also, it influences congestion and fairness in channel usage.

Subsequently a great deal of research has gained importance in the design of power and delay aware MAC protocols for WSNs for minimising battery usage and packet latency. I. Demirkol *et al.* [30] stated that collision, overhearing, control packet overhead, idle listening and overemitting are major sources of energy wastage and delay in MAC protocol design for WSNs.

Deterministic protocol such as TDMA suggested by Wendi. B. Heinzelman *et al.* [31] appear to be promising owing to negligible number of collisions and low power operation by scheduling their transmission times. When a node has no data to send, it still turns on the radio during its scheduled slots. The node consumes more energy as it operates in idle mode. Subsequently Heinzelman *et al.* proposed E-TDMA, an improved form of TDMA scheme by keeping its radio off during its allocated time slots to minimise energy consumption. However such schemes suffer from scalability problem in large and dense WSNs and also endure suboptimal use of wireless channel. Moreover, during low contention, TDMA scheme gives much lower channel utilisation and higher delays.

Later J. Li and G.Y. Lazarou [32] suggested the BMA MAC scheme, an enhancement of E-TDMA scheme by allocating dynamic time schedule for nodes to reduce the energy wastage due to idle listening and collisions for event driven sensing applications. Further, Leonard Kleinrock and Fouad A. Tobagi [33] investigated CSMA based MAC protocols to present superior performance in terms of channel utilisation. The nodes, using CSMA, pre-allocate transmissions and compete for a shared channel resulting in probabilistic coordination. Thus, collisions among one hop neighbours can be greatly reduced with carrier sensing before transmission. However collisions can happen in any two hop neighbourhood of a node. This problem referred to as the hidden terminal problem, cause serious throughput degradation and lack energy conservation mechanisms.

Further S. Singh and C.S. Raghavendra [34] developed a power aware multi access protocol with signaling scheme to reduce unnecessary power consumption by turning overhearing nodes to sleep. The protocol needs a separate control channel for sleep scheduling to avoid packet overhearing but it is suboptimal and inherently resource hungry. The reason is that it consumes extra resources for the signaling channel and also idle listening.

Subsequently Wei Ye *et al*. [35,36] formulated a Sensor MAC (SMAC) protocol to avoid idle listening. It is an IEEE 802.11 inspired CSMA MAC protocol which uses Request-To-Send/Clear-To-Send (RTS/CTS) handshake and addresses the problem of battery power conservation by periodic listening and wake up. The duty cycle with long active periods makes it inefficient in terms of battery wastage. Later, attempts have been made to integrate adaptive listening and scheduling to SMAC to minimise collision and power consumption. However, the use of explicit synchronisation frames for global synchronisation is an ineffective technique.

T.V. Dam and K. Langendoen [37] developed Timeout MAC (T-MAC) that exploits RTS-CTS-DATA and acknowledgement (ACK) exchange with adaptive duty cycle to save energy. It is an enhancement to SMAC, which dynamically minimises idle listening and wakeup durations. Although T-MAC provides better performance under variable loads, the synchronisation of the listen periods within virtual clusters is broken, resulting in larger energy consumption.

Further Jussi Haapola [38,39] suggested a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) based MAC protocol (referred as nanoMAC with sleeping schemes) to conserve energy and also compared its performance with SMAC based protocols [40]. It is clearly depicted that the nanoMAC protocol outperforms SMAC scheme. Moreover the synchronisation is handled in the RTS, CTS and ACK frames in nanoMAC and no extra listening is required per transmitted data packet. Hence, energy of sensor network can be saved significantly. Furthermore, the energy realm of the nanoMAC protocol [41] is evaluated with single hop and multihop communication based on Zach Shelby *et al.* [42] model.

However the use of a standalone TDMA or CSMA based MAC protocol for large scale networks would not be practical and promising in reducing energy consumption and packet delay. Subsequently, A. El-Hoiydi [43] introduced the spatial TDMA and CSMA with preamble sampling protocol in which all sensor nodes are defined to have two communication channels. The data channel is accessed using TDMA, whereas the control channel is accessed by CSMA.

Further C.C. Enz *et al.* [44] suggested the wise MAC protocol which requires only a single channel. Wise MAC protocol uses np-CSMA with preamble sampling [43] to reduce idle listening. In preamble sampling technique, a preamble is used to alert the node to receive each data packet. All nodes in the network, sample the medium with a common period but their relative schedule offsets are independent. If a node finds the medium busy after it wakes up, sample the medium and continue to listen until it receives a data packet or the medium becomes idle again. However, the receiver may not be ready at the end of preamble due to interference which cause overemitting-type energy wastage. In addition, the hidden terminal problem persists in the wise MAC model as in the spatial TDMA and CSMA with preamble sampling algorithm. This is because wise MAC is also based on np-CSMA. This problem results in collision when one node starts to transmit the preamble to a node that is already receiving another nodes transmission.

A. Ephermides and O. A. Mowafi [45] explored the switching between TDMA and CSMA according to level of contention in the network for WLAN environment using a Probabilistic TDMA (PTDMA) scheme. However the technique does not deal with difficulties that TDMA faces in adhoc sensor network such as time synchronisation error and interference irregularity. Sensor networks undergo frequent topology changes due to time varying channel conditions, physical environmental changes, battery outage and node failure. These failures can drastically reduce the performance of PTDMA. In a network, where only a subset of nodes is active data source, PTDMA scheme offers lower channel utilisation and does not behave like CSMA.

Subsequently Injong Rhee *et al.* [46,47] devised a link scheduling scheme such as Zebra MAC (Z-MAC) for resolving channel contention. Z-MAC uses the advantages of both CSMA and TDMA MAC. The main feature of Z-MAC is that it can adapt to the level of contention in the network and behaves like CSMA and TDMA under low contention and under high contention respectively. Hence, the protocol becomes robust to dynamic topology changes and time varying channel conditions and slot assignment failures commonly occurring in sensor networks. The problem with Z-MAC is that it needs local synchronisation among senders in two hop neighbourhood. Hence a simple local synchronisation scheme is required where each sending node adjusts its synchronisation frequency based on its current data rate and resource budget.

Mustafa Shakir *et al.* [48] attempted to study the performance of hybrid MAC layer approach in terms of combining the TDMA and CSMA with preamble sampling to get an optimised performance. The distinctive feature of the approach is its robustness to synchronisation to minimise channel collision. It has been proved that CSMA gives better performance for lesser number of nodes as in case of cluster head to cluster head communications. Also, the hybrid MAC approach is suitable in getting the best optimum performance by utilising TDMA for intra-cluster communication and CSMA with preamble sampling for inter-cluster communication. However, an energy efficient MAC scheme has not been presented to improve the performance to enhance cluster network lifetime.

In the harsh working wireless environments, channel fading, interference and radio irregularity often degrade the signal transmission and increases bit error rate. Diversity techniques have been widely used for suppressing the channel fading and interference in wireless networks. In physical layer, MIMO systems were proposed to use multiple transmitting and receiving antennas for signal transmission. Mohinder Janakiraman [49] demonstrated that multi input multi output systems support high data rates under the same transmit power budget and bit error rate performance requirements as that of single input single output system with minimum energy consumption.

MIMO techniques require complex transreceiver circuitry and signal processing, leading to large energy consumption at the circuit level. This has precluded the application of MIMO to energy limited WSNs. Moreover, physical implementation of multiple antennas at a small node may not be realistic. As a solution to the problem, cooperative MIMO has been explored by Shuguang Cui *et al.* [50] to improve MIMO capability in a network of single antenna where the individual single antenna nodes cooperate on information transmission and reception for energy efficient communication. Also, relative performances of MIMO and SISO systems in terms of total energy and delay have been critically evaluated. It has been proved that cooperative MIMO based sensor network provide better energy optimisation and smaller end-to-end delay than SISO scheme for transmission distance larger than a given threshold.

Subsequently Sudharman K. Jayaweera [51,52] developed a semi-analytical method to obtain the energy consumption values of both virtual MIMO and SISO based sensor networks taking into account the effect of extra overhead required in MIMO systems. The energy and delay efficiencies of the virtual MIMO based sensor network for different channel propagation condition were computed and compared with traditional SISO based sensor network. It has been proved that the virtual MIMO based communication architecture can offer substantial energy savings in a wireless sensor network. However the system needs to be designed judiciously taking into account the transmission distance, rate optimisation as well as end-to-end delay constraints.

Further George N. Bravos *et al.* [53,54] examined the energy efficiency of a MIMO based sensor network in comparison to SISO multihop network. The energy efficiency mainly depends on the channel conditions and the distance to destination node. Hence, an attempt has been made to arrive at analytical expressions to compute threshold values of above parameters which determine the areas where the MIMO based structure outperforms simple SISO multihop system. It has been proved that the MIMO outperforms multihop system when distance (d) between the source and destination node and path loss factor (n) are greater than

50m and 2.7 respectively. However, simple SISO multihop approach shows better performance than MIMO in terms of energy consumption, when d < 10m and n < 2.4. Subsequently, a simple Cooperative Node (CN) selection algorithm has been proposed to achieve additional energy gains in the MIMO approach.

Further Yong Yuan *et al.* [55] examined a multihop virtual MIMO communication protocol using cross layer design to jointly improve the energy efficiency, reliability and end-to-end Quality of Service (QoS) provisioning in WSN. The protocol extends LEACH scheme suggested by Wendi R. Heinzelman *et al.* [56] by incorporating the cooperative MIMO communication, multihop routing and hop-by-hop recovery schemes. The overall energy consumption per packet transmission is modeled using the protocol to arrive at optimum set of transmission parameters. The end-to-end latency and throughput of the protocol are modeled in terms of Bit Error Rate (BER) performance of each link by cross layer design. A nonlinear programming model is developed to find the optimal BER performance of all links. The particle swarm optimisation algorithm is also employed to solve the problem. It is proved that this approach is effective in minimising energy consumption and end-to-end QoS.

Subsequently Azzedine Boukerche and Xin Fei [57] presented a multihop virtual MIMO scheme [51,52] and analysed the energy cost affected by the construction process of virtual MIMO in a large WSN. However, the impacts of transmission synchronisation error and additive noise in cooperative reception techniques have not been considered in the study.

The energy efficiency of cooperative MIMO transmissions is achieved using Alamouti and space time codes. The space time block code and space time trellis code are two outstanding examples of transmit diversity schemes for multiple antenna flat fading channel. V. Torakh *et al.* [58] devised space time block code to operate on a block of input symbol producing a matrix output whose columns and rows represent time and antennas respectively. Unlike traditional single antenna block codes for the Additive White Gaussian Noise (AWGN) channel, most space time block codes do not provide coding gain. Their key feature is the provision of full diversity with extremely low encoder/ decoder complexity. Subsequently Andrej Stefanov and Tolga M. Duman [59] presented space time trellis codes that operate on one input symbol at a time producing a sequence of vector symbols whose length represents antennas. Similar to traditional Trellis Coded Modulation (TCM) for the single antenna channel, space time trellis codes provide coding gain. The disadvantage is that they are extremely difficult to design and also requires a computationally intensive encoder and decoder.

S. Sandhu *et al.* [60] compared the performance of Space Time Block Code (STBC) and Space Time Trellis Code (STTC) in terms of frame error rate keeping the transmission power, spectral efficiency and number of trellis states fixed. It is stated that a simple concatenation of space time block codes with traditional AWGN trellis codes, outperforms some of the best known space trellis at Signal to Noise Ratios (SNRs) of interest. The above space time coding techniques considered neither the impact of transmission synchronisation error nor the additive noise in cooperative reception.

Sumanth Jagannathan *et al.* [61] investigated the effect of time synchronisation errors on the performance of the cooperative MISO systems. It has been concluded that the cooperative MISO scheme has good tolerance up to 10% clock jitter. However, this study is limited to two transmission antennas only. Also, the Channel State Information (CSI) was considered to be known in the receiver and the effect of synchronisation error is presented for low range SNR. Moreover, the impacts on multihop networking, reliable transmission and QoS provisioning for the virtual MISO scheme, have not been considered.

Tuan Duc Nguyen *et al.* [62] extended the MIMO cooperative principle to 3 and 4 transmission antennas using Tarokh STBC to evaluate the system performance. The cooperative reception technique quantizes the received symbol and forwards the bit sequences to the destination node. This increases the amount of data transmitted and the circuit energy consumption. Hence cooperative reception techniques derived from amplify and forward strategies were developed to achieve better energy efficiency. It is proved that the performance degradation in cooperative MIMO is negligible for a small synchronisation error range at cooperative transmission and a reasonable amplification factor in reception.

Although cooperative MIMO schemes have been explored to combat fading and energy consumption, the effects of the radio channel suggests the need of MAC protocol that can suit cooperative MIMO system. A combination of practical MAC protocol and an efficient cooperative MIMO scheme for cooperative transmission has been examined by Haiming Yang *et al.* [63]. The MAC protocol combined the advantages of distributed MACs centralised system. Sleep cycles are not used to ensure that always cooperative nodes are available to satisfy the delay requirements of time critical applications. Analytical models were developed for the combined scheme to evaluate the performance of the protocol in terms of its transmission error probability, energy consumption and delay. The proposed cooperative MIMO MAC protocol outperforms point to point communications at low transmission powers.

Further Mohd Riduan Ahmad *et al.* [64] attempted to evaluate the MAC protocol proposed by Haiming Yang *et al.*[63] using three cooperative MIMO schemes such as beam forming, STBC and spatial multiplexing. The MAC protocol in all the schemes considered the transreceivers as always being on and the networks are perfectly synchronised. It has been shown that SISO scheme is more energy efficient and has lower latency at higher regions of transmission power. However, the three cooperative MIMO schemes are more energy efficient and outperform SISO scheme at lower regions. Also, it is shown that the beam forming cooperative scheme with two transmit nodes is the optimal scheme in terms of energy efficiency and lower packet latency. Although, transmission energy is reduced and the deep fading threat is reduced or eliminated, the idle listening problem has not been addressed. Also, the imperfect synchronisation due to clock jitter is not considered.

Subsequently Mohd Riduan Ahmad *et al.* [65] investigated a cooperative low power listening MAC for the cooperative schemes and evaluated their performance in terms of energy consumption and latency. Also, performance of cooperative low power listening MAC was compared with cooperative always-on MAC and always-on SISO. The impact of jitter difference, check interval and the number of cooperative nodes on the total energy consumption and latency are investigated. It was observed that cooperative low power listening MAC with optimal beam forming is the most promising configuration and it is optimal when the number of cooperative nodes are 2 and jitter difference is below 0.6 T_b.

Further Mohd Riduan Ahmad *et al.* [66] studied the impact of transmission delay differences between cooperating nodes on bit error rate performance and energy consumption of sensor nodes. A quasi Rayleigh flat fading channels for local transmission between nodes were considered and its transmission delay effects are determined. It is evident that the traditional non-cooperative approach is more energy efficient than cooperative strategy in the range beyond 0.75 T_b.

In addition to the design of MIMO MAC transmission system, the key challenges faced in WSNs are node coordination in sending and receiving group, distributed space time coding in sender and data combining at the destination. In cooperative MIMO transmission, the destination needs to combine multiple receiving signals and make signal detection. In the link layer, code combining techniques have been considered. T.E. Hunter and A. Nosratinia [67] devised coded operation for transmission between two sending node and one receiving node. In each time slot, only one of the sending nodes transmit a data block that contains N_1 bits from its own coded bits and N_2 bits from its partner. The receiver then combines the received bits from the two senders by code combining. However, the coded cooperation for cluster based network was not clearly defined.

Subsequently Su Yi *et al.* [68] investigated the coded cooperation with multiple receiving nodes in a cluster based cooperative network. In this scheme, sending node transmits packet to the receiving cluster and each cluster member relays its signal copy to the destination. The destination node uses code combining techniques to decode the original information bits. Analytical interpretations show that the link layer reliability is greatly improved with the same power consumption.

Hsin Yi Shen and Shivkumar Kalyanaraman [69] developed an asynchronous cooperative MISO scheme to address the node coordination problem in sending and receiving group. Instead of using perfect synchronisation technique, cooperative transmission is considered to be asynchronous. Each member in transmitting cluster relays signal to the receiving cluster after obtaining information from source node. A general decision feedback equalizer is used in the receiving cluster members to equalize the received MISO signal and detect as soft symbols. The receiving cluster members send soft decision outputs to the destination node. The decision node combines the soft decision outputs and makes hard decision detection for transmitted information. A simple capacity analysis has been developed to evaluate the performance of cooperative MIMO transmission system and direct system in terms of capacity ratio. The result shows that cooperative system has larger capacity than direct transmission.

Subsequently Hsin Yi Shen *et al.* [70] devised a concrete scheme that combines STBC and cooperative code combining. The uses of STBC and code combining address the issues of transmitter and receiver diversity in cooperative MIMO system. Once the sending and receiving groups are formed, STBC are deployed in the sending group to utilise transmitter diversity. The error control code combining is used in the destination to combine the signals from nodes in receiving group to achieve receiver diversity. It has been proved that the system provides reliable and efficient transmission by leveraging MIMO diversity gains.

Further Hsin Yi Shen *et al.* [71] formulated a distributed system for cooperative MIMO transmissions that utilises space time block coding and code combining in the sending and receiving groups. A pseudo noise sequence based uncorrelated pilot symbol generation with iterative updates has been incorporated to estimate the multiple Carrier Frequency Offsets (CFO) from received mixed pilot signals. Also, the Minimum Mean Square Estimator (MMSE) detector for receiving STBC coded data under multiple CFO is studied. The BER and total energy consumption of the system is estimated and compared with other cooperative designs. The result shows that the proposed approach significantly improves BER and energy efficiency.

To facilitate cooperative MIMO transmissions with high degree of performance improvement, Jong Whoi Shin *et al.* [72] developed a threshold based MAC protocol for distributed wireless systems. The protocol uses a threshold scheme that is updated dynamically based on the queue length at the sending node. Transmissions in the protocol proceed only when the expected transmission BER is lower than the cooperative threshold BER value. The sending and receiving group sizes are selected on the basis of cooperative threshold to achieve the minimum energy consumption. The performance of the protocol is compared with that of point to point and fixed group size MIMO MAC protocols in terms of energy consumption and transmission delay. However, an efficient coding scheme has not been considered with the protocol to improve energy efficiency.

Furthermore attempts have been made to design an efficient routing scheme for sensor networks to maximise the lifetime. Conventional routing techniques such as direct and multihop transmission schemes incur energy loss that is quite extensive depending on the location of sensor nodes relative to sink. Jamal N. Al-Karaki and Ahmed E. Kamal [73] critically reviewed various routing protocols for sensor networks and grouped the protocols based on the network structure and protocol operation.

Data-centric routing is a commonly utilised approach that uses attribute based addressing to perform the collective sensing task for sensor network. In this routing, sensor nodes are assigned tasks based on interest disseminations that originate from another node in the network. The Sensor Protocol for Information via Negotiation (SPIN) [74] and directed diffusion [75] are the two protocols based on data-centric routing. In SPIN, the sensor nodes that have data to send, broadcast an advertisement to their neighbours and send the actual data only to those nodes that are interested. To reduce the energy expended in the broadcast of advertisements, the SPIN protocol family use meta-data descriptors, which describe the actual sensor data in a more compact size. The directed diffusion paradigm, however, uses a slightly different type of data-centric routing. In this scheme, the sink broadcasts the interest to all sensor nodes in the network. Each sensor node stores the interest in a local cache and uses the gradient fields within the interest descriptors to identify the most suitable path to the sink. Although, data- centric routing approach provides a reliable and robust solution to wireless sensor networks, there are still some shortcomings associated with protocols utilising this technique. In the worst case, both SPIN and directed diffusion suffer from the amount of overhead energy spent in activities such as advertising, requesting and gradient setup. Furthermore, the excessive time spent in such activities might not suit some applications that require the sensor nodes to respond quickly in an emergency situation.

The more apt solution for such scenarios is a clustering based protocol. However, the application of conventional clustering to WSN does not improve the network lifetime. It is due to the fact that the conventional clustering scheme assumes the cluster heads to be fixed and thus makes them to be high energy nodes. To alleviate this deficiency, an adaptive clustering scheme called LEACH is proposed by Fan Xiangning and Song Yulin [76] that employs the technique of randomly rotating the role of a cluster head among all the nodes in the network. It has been shown that LEACH scheme provides significant energy savings and prolonged network lifetime over fixed clustering.

A centralised version of LEACH (LEACH-C) was proposed by Mohammad Hammoudeh *et al.* [77]. Unlike LEACH, where nodes self-configure themselves into clusters, LEACH-C utilises the sink node for cluster formation. Subsequently, Do Hyun Nam and Hong Ki Min [78,79] formulated the Round Robin Cluster Head (RRCH) routing that fixes the cluster and selects the head node in a round robin method. The RRCH approach is an energy efficient method that provides consistent and balanced energy consumption in each node of a generated cluster to prevent repetitious set-up process.

Stephanie Lindsey and Cauligi S. Raghavendra [80,81] formulated a Power Efficient GAthering in Sensor Information Systems (PEGASIS). It is a near optimal chain based routing protocol where each node communicates only with a close neighbour and transmits data to the sink to reduce the amount of energy spent per round. Siva D. Muruganathan *et al.* [82] investigated a centralised routing protocol, namely, Base station Controlled Dynamic Clustering Protocol (BCDCP) to distribute the energy dissipation evenly among all sensor nodes to improve network lifetime and average energy savings. The performance of BCDCP scheme is compared with that of LEACH, LEACH-C and PEGASIS. It is evident that BCDCP scheme reduces overall energy consumption and improves the network lifetime.

Vivek Mhatre and Catherine Rosenberg [83] presented a cost based comparative study of single hop homogeneous and heterogeneous clustered sensor networks. The hardware as well as the battery cost of the nodes was taken into account in the analysis. A generalisation of LEACH called multihop LEACH, which uses multihop communication within the cluster is analysed. It is concluded that LEACH with multihop transmission is more energy efficient than conventional single hop LEACH.

The homogeneous sensor network considered so far suffered from poor performance and scalability. Subsequently, Xiaojiang Du and Fengjing Lin [84] suggested an efficient routing protocol to improve the network performance using heterogeneous sensor nodes. Using this protocol, long range transmissions to sink were performed by powerful cluster heads called H-sensors and L-sensors send packets to nearby cluster heads. The results demonstrated that the cluster based approach using Heterogeneous Sensor Network (HSN) performs better than directed diffusion and mesh protocol. Further Xiaojiang Du and Fengjing Lin [85], formulated the cluster head relay routing protocol for HSN to lower total energy consumption, achieve high packet delivery ratio and lesser delay.

Rui Wang *et al.* [86] formulated an energy efficient clustering algorithm based on Virtual Area Partition (VAP) for heterogeneous WSNs. The network with VAP provides balanced communication load between clusters, reduces the energy consumption of sensor node and prolongs the network lifetime when compared with LEACH scheme.

Further Georgios Smaragdakis *et al.* [87] developed a heterogeneous Stable Election Protocol (SEP), to prolong the time interval before the death of the first node. SEP protocol is based on weighted election probabilities of each node to become cluster head according to the remaining energy. The behaviour of sensor nodes becomes unstable, once the first node dies. It is found that SEP yields longer stability region due to higher energy nodes.

Subsequently P.T.V Bhuvaneswari *et al.* [88] suggested Sensor Protocol for Energy Aware Routing (SPEAR) for the election of cluster heads based on energy as well as spatial distribution. The simulation results reveal that SPEAR yields longer stability periods due to heterogeneous aware nature. The consequent higher average throughput and longer network lifetime make the protocol an effective alternative to the existing routing protocols in WSNs.

Further Chiu Kou Liang *et al.* [89] explored a Cluster based Minimal Spanning Tree with Degree Constrained (CMST-DC) to collect information efficiently in a sensor network. Analysis shows that the CMST-DC protocol is efficient and ensures maximum utilisation of network energy, longer network lifetime and lesser time to complete a round.

Subsequently Feng Zhao *et al.* [90] analysed the energy consumption in typical clustering protocols and claimed that energy consumption is not evenly distributed among nodes. Thus some of the nodes in the network die quickly which leads to reduction in network lifetime. This has prompted to envisage a new energy balanced strategy in clustering protocols. The strategy assigns the head communication load to sink by detecting the energy consumption in the cluster heads. The evenly distributed energy among the nodes is realised by controlling the head consumption.

Further L.S. Jayashree *et al.* [91] developed an energy efficient load balanced clustering technique for heterogeneous wireless sensor networks. An attempt has been made to consider the combined effect of communication distance and load at each cluster head to suggest an optimal assignment to maximise the overall network lifetime. The performance of the system is evaluated and the results are compared with unbalanced clustering in terms of network stability. It is proved that the protocol is more effective in terms of energy efficiency and network stability than unbalanced clustered networks.

Also, Xiaoya Li *et al.* [92,93] developed and analysed the routing protocol based on Residual Energy and Energy Consumption Rate (REECR) for heterogeneous wireless sensor network. The protocol was not very ideal to balance the stability of energy consumption of nodes. Consequently, a zone based REECR routing protocol has been devised to balance the energy consumption of nodes in the network.

Ming Yu *et al.* [94] presented a new energy efficient dynamic clustering technique for large scale sensor networks. By monitoring the received signal power from its neighbouring nodes, each node estimates the number of active nodes in real-time and computes its optimal probability of becoming a cluster head, so that, the energy spent in both inter and intra-cluster communication can be minimised. Based on the clustering architecture, an energy efficient and power aware multihop routing algorithm has been suggested to prolong the network lifetime. The clustering algorithm scales well and converges faster for large scale dynamic sensor network.

Subsequently MIMO techniques are incorporated in the cluster based sensor network to overcome the effects of channel fading and interference. Aitor del Coso *et al.* [95] explored cooperative diversity in multihop WSN for clustered topology. Multihop transmission is carried out by concatenating single cluster-to-cluster hops. A time division relaying scheme has been devised to exploit transmit diversity. At the receiving cluster a distributed multiple antenna reception protocol is analysed based upon the selection diversity algorithm. The end-to-end outage probability has been evaluated for the multihop WSN. It is shown that the multihop scheme provides diversity equivalent to a MIMO system and significantly reduces the energy consumption with respect to the non-cooperative channel.

Zhong Zhou *et al.* [96] suggested a cooperative transmission scheme based on distributed space time block coding. The performance is analysed with the assumption that error detection is done at the packet level and nodes decode received packets cooperatively. Based on the performance analysis, an optimisation technique has been adopted to minimise the overall energy consumption. It is evident that having more nodes in a cluster may not be energy efficient due to extra circuit energy consumed by potential cooperative nodes. It is concluded that the optimal number of sensors in the cluster varies depending on Packet Error Rate (PER) requirements. Also, it is shown that significant energy savings can be achieved even with strict requirements on throughput and delay than non-cooperative transmission.

An energy efficient adaptive rate cooperative MIMO selection scheme was developed by Irfan Ahmed *et al.* [97,98] for uniform load distribution in cluster based wireless sensor network. The intrinsic data flow direction in multihop cluster based sensor networks cause uneven load distribution in the network. The transmit clusters and the clusters near the sink carry more network traffic than the other clusters. Hence, the load based joint adaptive selection of rate and cooperative nodes in cluster devised render uniform energy consumption in the network. The proposed communication architecture offers substantial energy savings in the wireless sensor network maintaining the required bit error rate.

Although cooperative diversity enhances transmission energy efficiency, the involvement of more than one transmitting sensor increases electronic energy consumption. So far, cooperative transmission has been studied mostly under the assumption of perfect synchronisation. The overhead synchronisation, complexity and energy efficiency are to be justified. Xiaohua Li *et al.* [99] suggested a typical networking/communication protocol for WSNs i.e., LEACH to address asynchronous condition without loss of generality. LEACH protocol supports cooperative transmissions especially well because of formation of clusters and cluster head than other routing protocols. The energy efficiency of the scheme is analysed as a tradeoff between the reduced transmission energy consumption and increased electronic and overhead energy consumption. It is concluded that LEACH protocol with cooperative transmission can enhance energy efficiency and lifetime of WSNs.

However the protocol does not take into consideration the multihop routing and distributed operation in WSNs. Hence, Yong Yuan *et al.* [100] devised the scheme extending the LEACH protocol to enable the multihop transmissions among clusters by incorporating a cooperative MIMO scheme into hop-by-hop transmissions. The scheme gains effective performance improvement in terms of energy efficiency and reliability with adaptive selection of cooperative nodes and coordination between multihop routing for cooperative MIMO transmissions. The optimal parameters to minimise the overall energy consumption is found using the devised energy consumption model. It is evident from the results that the multihop routing scheme can effectively save energy and prolong the network lifetime.

Though multihop transmissions were used among clusters for virtual MIMO protocol, the results indicate that performance of the system decreases dramatically, when the location of sink node is far away from the network deployment area. Subsequently, Wenqing Cheng *et al.* [101] studied the impacts of cooperative MIMO techniques on cluster formation and developed a cooperative MISO transmission scheme based on LEACH protocol. An optimisation model was developed to find the optimum network parameters. It is shown that the performance of energy efficiency and the network lifetime can be remarkably improved than traditional LEACH scheme.

Although Wenqing Cheng *et al.* [101] investigated cooperative transmission in LEACH protocol, the assumption of perfect data aggregation based on ideal data correlation is not practical in most applications. Hence, Tianshi Gao *et al.* [102] suggested a new load balanced cluster based cooperative MIMO transmission scheme for remote environment surveillance taking imperfect data aggregation into consideration. In this scheme, a two layer hierarchy is formed by clustering and the cluster heads perform local data aggregation to balance communication loads and transmit data back to the sink. Results have indicated that the cooperative MIMO scheme can distribute the energy dissipation more evenly throughout the network and achieve higher energy efficiency.

2.3 SUMMARY

It is evident from the critical review of literature that exhaustive research has been already done by several researchers to efficiently utilise the battery resources of sensor nodes deployed in a harsh environment. The challenges and research issues at the physical, data link, network and application layer of the protocol stack of the sensor network has been extensively studied for the cluster based network applications. Several efforts have been made to overcome interference, radio irregularity and channel fading to improve the lifetime performance of the WSNs. Various MAC schemes have been explored for the network to share the radio channel efficiently and to minimise the collisions during packet transmission. Further, to coordinate the actions of sensor network in a fading environment, site diversity techniques have been exhaustively investigated to enhance the performance of WSN. Subsequently, to forward the data from the sensing field to the remote sink, various routing mechanisms are exploited to improve the network lifetime.

However, much attention has not been focused on the literature in design of cluster based MAC and routing incorporating diversity schemes have not been explored to effectively handle the energy consumption issue of the sensor network. Hence, in the present work, an attempt has been made to enhance the energy efficiency of cluster based WSN by employing an efficient inter and intra-cluster MAC protocol, cooperative MIMO MAC schemes and cooperative MIMO routing scheme to share the wireless medium effectively.

CHAPTER 3

HYBRID MAC PROTOCOL

3.1 INTRODUCTION

Wireless sensor networking is a novel communication paradigm involving devices with low complexity that has limitations on processing capacity, memory and severe restrictions on power consumption [28,29]. The traffic in sensor network is often bursty and its energy wastage results from collisions, overhearing, control packet overhead and idle listening to the radio channel [30]. Thus an effective medium access control protocol is essential in determining the radio channel. The pertinent solution to save energy is to use a cluster based approach for the MAC scheme [31].

From the perspective of MAC layer the clustered network is divided into two distinct parts i.e., intra and inter-cluster domain. This work suggests a novel hybrid MAC approach with BMA and nanoMAC for intra and inter-cluster domain respectively to reduce energy consumption. The main feature of the hybrid MAC protocol is that it can adapt to either high or low level of contention in the network. The performance of the proposed hybrid MAC protocol is evaluated to maximise the lifetime of the network and is compared with np-CSMA and conventional TDMA, E-TDMA scheme.

3.2 PROPOSED MAC PROTOCOL SYSTEM MODEL

Clustering scheme organises the nodes of the sensor network into two virtual domains, such as intra-cluster and inter-cluster domain as in Fig.3.1. In the intra-cluster domain, the nodes sense the data and communicate with the cluster head directly within the cluster. Since the radio channel has high contention due to large number of sensors in the intra-cluster domain [48], the TDMA based MAC (BMA) protocol is utilised for achieving high energy efficiency.

In the inter-cluster domain, the cluster head node communicates with the sink either directly (single hop) or through other cluster head nodes (multihop). The number of nodes contending for the radio channel in inter-cluster is lesser compared to intra-cluster domain [43,48], and a CSMA based MAC protocol (nanoMAC) is utilised for data transmission.

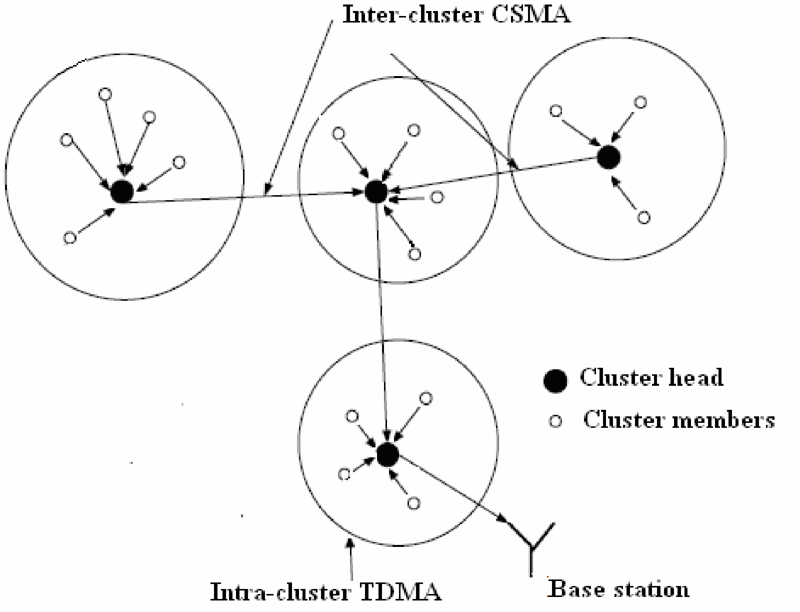

Fig.3.1. System model of hybrid MAC protocol

The frame structure of the hybrid MAC protocol is shown in Fig.3.2. In the intra-cluster domain, the cluster head assigns the time schedule to its nodes for data transmission. The time slot is subdivided into mini-slots equal to the number of nodes in a cluster. This mini-slot carries one-bit information of a node to determine whether they have the sensed data or not. If the node has no sensed data its time slot is allocated to other nodes that have data to transmit. In inter-cluster domain the cluster head nodes that have data to transmit performs Carrier Sense (CS) before transmission. If a head node fails to get the medium it goes to sleep and wakes up after a random time period and listens for the channel again. This feature contributes to increasing the robustness of the hybrid MAC protocol to synchronisation and topology changes while enhancing its scalability to contention.

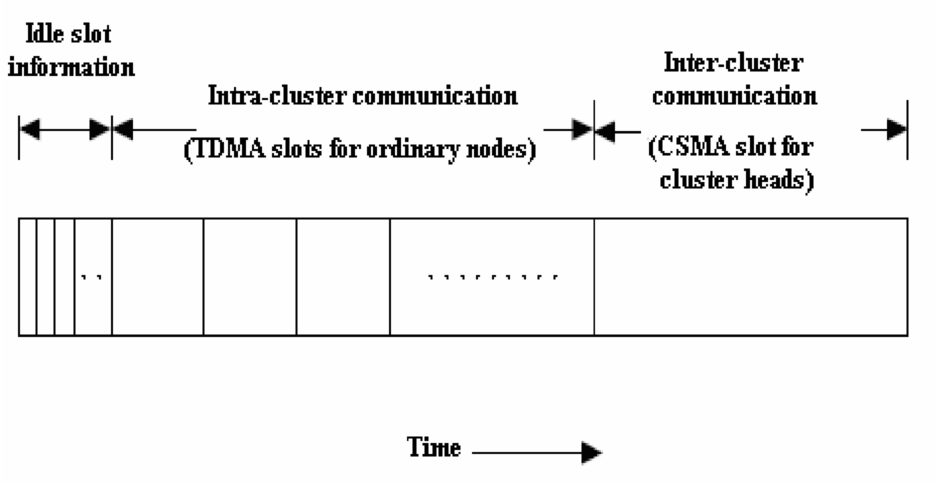

Fig.3.2. Hybrid MAC frame structure

3.3 MAC PROTOCOL FOR INTRA-CLUSTER DOMAIN

In conventional TDMA scheme, a node turns on its radio during its assigned slot whether it has data to transmit or not, resulting in higher energy consumption. To reduce the energy consumption, E-TDMA scheme is used, in which the node turns its radio off when it has no data to transmit. In addition, assigning dynamic time slot according to unpredictable traffic variations is difficult with conventional TDMA and E-TDMA scheme [43]. To efficiently assign the time schedule and minimise the energy consumption, BMA MAC protocol is suggested for intra-cluster domain.

3.3.1 BMA MAC Protocol

The main objective of the BMA MAC protocol is to reduce the energy consumption due to idle listening and maintain low latency. In clustering approach, the data transmission of the non-cluster head nodes is organised into rounds [15,31]. Each round consists of cluster set-up phase and steady-state phase as shown in Fig.3.3.

i) *Set-up phase*

During set-up phase, each node decides whether to become a cluster head based on its energy level. Elected cluster heads broadcast an advertisement message to all other nodes claiming to be the new cluster head by using non-persistent CSMA. Each non-cluster head node joins the cluster in which communications with the cluster head requires minimum amount of energy. Once the clusters are built, the system enters into the steady-state phase.

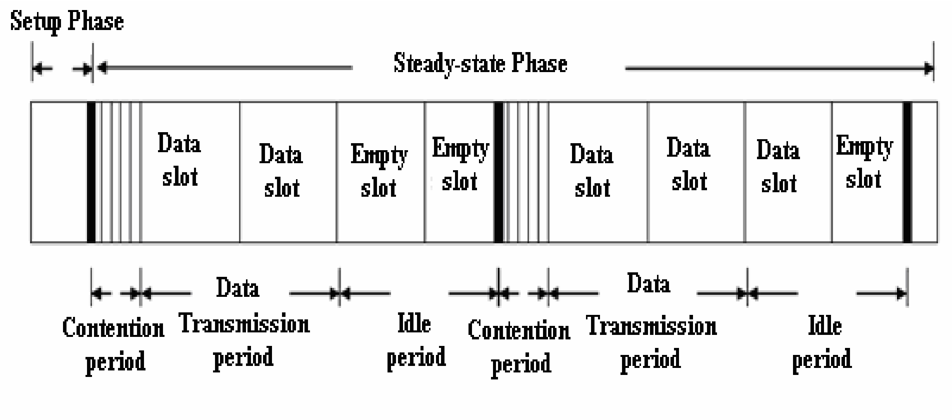

Fig.3.3. Transmission periods of BMA MAC protocol

ii) *Steady-state phase*

The steady-state phase is divided into sessions. Each session consists of a contention period, a data transmission period and an idle period as in Fig.3.3. With N non-cluster head nodes in the cluster the contention period are exactly N slots. During each contention period, all nodes keep their radios on. Using BMA MAC each node is assigned a specific slot to transmit a one-bit control message if it has data to send.

After the contention period, the cluster head broadcasts its transmission schedule to the non-cluster head nodes in the cluster and the system enters into the data transmission period. If the non-cluster head nodes have no sensed data, the system proceeds directly to an idle period, which lasts until the next session. The nodes keep their radios off during the idle periods to save energy.

When a session finishes, the next session begins with a contention period and the same procedure is repeated. The cluster head collects the data from all the source nodes and then forwards the aggregated and compressed data to the sink directly or via a multihop path. After a predefined time, the system begins the next round and the whole process is repeated.

3.3.2 Energy Model of BMA MAC

This model describes the energy consumed by the sensor node in intra-cluster domain [32]. In BMA protocol, the sensor nodes keep their radio ‘on’ during the whole contention period. After receiving the transmission schedule from cluster head, each source node sends its data packet to the cluster head over its scheduled time slot.

The energy consumed by each source node during a single session is given by

$$E_{sn} = P_t T_c + (N-1) P_i T_c + P_r T_{ch} + P_t T_d \tag{3.1}$$

where P_t, P_r and P_i are the power consumption during the transmission, reception and idle mode respectively

T_c is the time required to transmit/receive a control packet

N is the number of non-cluster head nodes within a cluster

T_{ch} is the time required for BMA cluster head to transmit a control packet

T_d is the time required to transmit/receive a data packet

Each non-source node stays idle during the contention period and keeps its radio off during the data transmission period. Thus, over a single session, the energy that it dissipates can be computed as

$$E_{in} = N P_i T_c + P_r T_{ch} \tag{3.2}$$

During the contention period of the ith session, cluster head node receives n_i control packets from non-cluster head nodes and stays idle for (N- n_i) contention slots. In the subsequent transmission period, the cluster head node receives n_i data packets from the non-cluster head nodes. Hence, the energy expended in the cluster head node during a single session is given as

$$E_{ch} = n_i (P_r T_c + P_r T_d) + (N - n_i) P_i T_c + P_t T_{ch} \tag{3.3}$$

where n_i is the number of source nodes in the ith session/frame

Therefore, the total system energy consumed in each cluster during the ith session is

$$E_{si} = n_i E_{sn} + (N - n_i) E_{in} + E_{ch} \tag{3.4}$$

Each round consists of k sessions, thus the total system energy dissipated during each round is computed as

$$E_{round} = \sum_{i=1}^{k} E_{si} \tag{3.5}$$

The average packet delay τ_d, is defined as the average time required for a packet to be received by the cluster head node and is given by,

$$\tau_d = \frac{NT_c + T_{ch} + n_i T_d}{n_i} \tag{3.6}$$

3.4 MAC PROTOCOL FOR INTER-CLUSTER DOMAIN

In conventional np-CSMA scheme [33], a node with a frame to transmit senses the channel using carrier sense. If the channel is detected busy, the node waits for a random time interval for transmission to avoid collision. When two users sense the channel idle at same time and transmit their frames, collision occurs. This requests for retransmission and results in high energy consumption of the sensor node. To minimise the energy consumption, nanoMAC protocol is suggested for inter-cluster domain.

3.4.1 Nano MAC Protocol

NanoMAC protocol is of CSMA/CA type and is non-persistent. With probability p, the protocol will act as non-persistent and with probability (1-p), the protocol will refrain from sending even before CS and schedule a new time to attempt for CS. Nodes contending for the channel do not constantly listen for the channel, contrary to the normal binary exponential backoff mechanism, but sleep during the random contention window.

When the backoff timer expires, the nodes wake up to sense the channel. This feature makes the CS time for nanoMAC short, and saves the energy of sensor nodes to a greater extent. With one RTS and CTS reservation, a maximum of 10 data frames can be transmitted using the frame train structure as in Fig.3.4. The data frames are acknowledged by a single, common ACK frame that has a separate ACK bit reserved for each frame. In this way, only the corrupted frames are retransmitted and not the whole data packet.

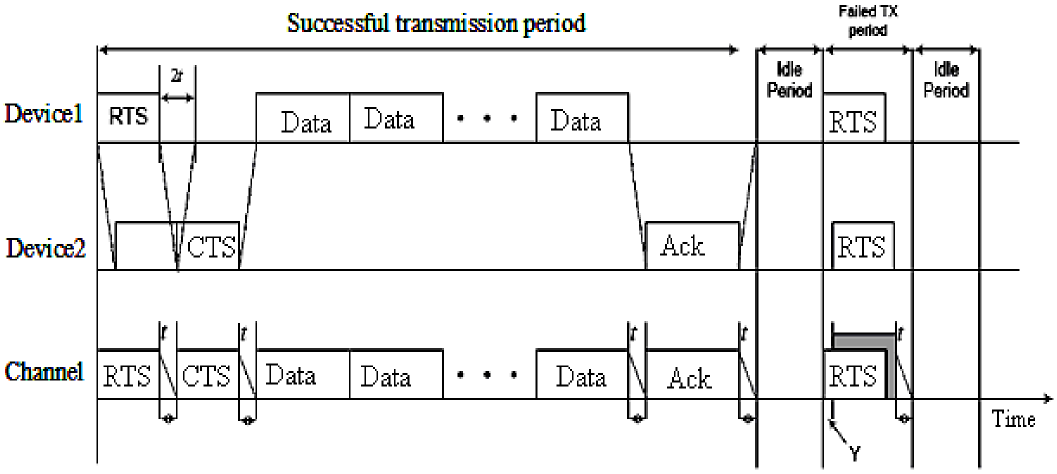

Fig.3.4. Transmission periods of nanoMAC protocol

3.4.2 Energy Model of NanoMAC

The transmission energy consumption model of nanoMAC protocol is shown in Fig.3.5. This model describes the energy consumed during data transmission taking into account the average contention times, backoff times and frame collisions [103-106]. There are four different states: Arrive, Backoff, Attempt and Success. Arrive state is an entry point to the system for a node to transmit new data. On every arrival to one of these states, energy is consumed. To reach the success state, all possible transitions starting from the arrival state and ending at the success state is calculated.

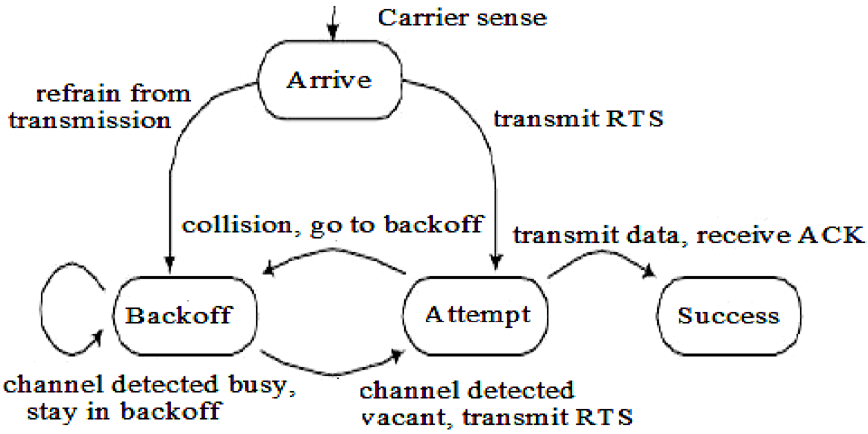

Fig.3.5. Transmitter energy model of nanoMAC protocol

On the arrival of data, when a device finds the channel busy, it refrains from its transmission, and reaches the backoff state. When the channel is clear upon CS, the sensor node transmits an RTS frame to the destination node and it waits for a CTS frame and reaches the attempt state. On successful transmission of the RTS and reception of CTS, a transition to the success state is made. The success state represents a successful data exchange with the destination.

When the RTS frame collides, the device returns to the backoff state and no new data transmissions are made during this failed period. Backoff state represents the device's waiting period, trying to acquire the channel again. When the device detects the channel as vacant or idle, it transits to the attempt state by sending a RTS frame. When the channel is detected busy, it stays in the backoff state and the process repeats.

The average energy consumption upon transmission from the point of packet arrival to the point of receiving an ACK frame is given by

$$E_{TX} = E_{arrive} + p_{prob1}E(A) + (1 - p_{prob1})E(B) \tag{3.7}$$

where E_{arrive} is the carrier sensing energy consumption when reaching the arrive state

$E(A)$ and $E(B)$ are the energy consumption on each visit by the node to attempt state and backoff state and are given by

$$E(A) = p_{prob2}E_{success} + (1 - p_{prob2})E(B) \tag{3.8}$$

and

$$E(B) = p_{prob3}E(A) + (1 - p_{prob3})E(B) \tag{3.9}$$

where $E_{success}$ is the expected energy consumption upon reaching the success state from the attempt state

$p_{prob\{1,2,3\}}$ are the different probabilities related to arriving to a certain state

The transmitter energy consumption can be simplified as

$$\begin{aligned} E_{TX} = {} & T_{CS}M_{RX} + p_b\left(T_{bb} + \frac{T_r}{2}\right)M_{Slp} + p_bE(B) + (1 - p_b)(1 - p_{ers})(T_{bp} + \frac{T_r}{2})M_{Slp} \\ & + (1 - p_b)p_{ers}E(A) + (1 - p_b)p_{ers}(T_{pr} + T_{rts})M_{TX} + (1 - p_b)(1 - p_{ers})E(B) \end{aligned} \tag{3.10}$$

where T_{CS} is the time required for carrier sensing

M_{RX} is the receiver power consumption

p_b is the probability of finding channel busy during carrier sense

T_{bb} is the incremented backoff time

$T_r/2$ is the average random delay

M_{Slp} is the sleep power consumption of transceiver

T_{bp} is the un-incremented backoff time

p_{ers} is the non-persistence probability of nanoMAC

T_{pr} is the time required to transmit a preamble

T_{rts} is the time required to transmit an RTS frame

M_{TX} is the transmitter power consumption

The receiver energy consumption model of a packet for nanoMAC protocol is shown in Fig.3.6. There are three different states: Idle, Reply and Received. When an RTS packet is received by the destination node, it transits to state Reply and forwards the CTS packet to the source. When the destination node receives the valid data packet from the source it reaches the received state and sends an ACK frame to the source node. When the CTS packet transmitted by the receiver collides, it stays in idle state.

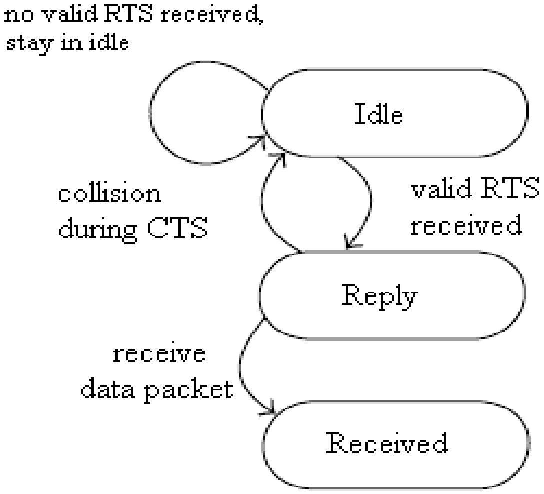

Fig.3.6. Receiver energy model of nanoMAC protocol

The average energy consumed by the receiver to receive data packet is given by

$$E_{RX} = E(I) = \frac{(\mu + p_s\theta)}{(p_s p_{senh})} \tag{3.11}$$

where E(I) is the energy incurred in each visit of node to idle state
μ represents the energy model transitions from state idle
θ represents the energy model transitions from state reply
p_s and p_{senh} are the probabilities of no collision during RTS or CTS transmission

The average packet delay τ_d, from the cluster head to the sink is calculated using Fig.3.5 and is given by

$$\tau_d = p_b\left[T_{bb} + \frac{T_r}{2} + E(B)\right] + (1-p_b)(1-p_{ers})\left[T_{bp} + \frac{T_r}{2} + E(B)\right] + (1-p_b)p_{ers}\left[E(A)\right] \quad (3.12)$$

The channel throughput S, is defined as the average number of successful frame transmissions per time interval T_f and is given by

$$S = \frac{\rho(T_{cp}+1)(1-p_{ers}+e^{-T_p\rho}p_{ers})}{\rho(1+(4+p_{ers})T_p+2T_{cp}+\frac{T_{ack}}{T_f})+p_{ers}e^{-T_p\rho}} \quad (3.13)$$

where ρ is the traffic intensity or normalised traffic offered to the channel
T_{cp} is the normalised time for transmission of control packets
T_p is the normalised propagation time
T_{ack} is the transmission time for acknowledgement

3.5 RESULTS AND DISCUSSION

The parameters considered for the simulation of hybrid MAC protocol is summarised in Table 3.1. The performance of the intra-cluster BMA MAC protocol and the inter-cluster nanoMAC protocol are evaluated in terms of traffic offered in the network, delay and energy consumption.

Table 3.1 Simulation parameters for nanoMAC and BMA MAC protocol

Parameter	Value
Data frame size of nanoMAC	41 bytes
Data frame payload of nanoMAC	35 bytes
Data packet size of BMA	1452 bytes
Data packet payload of BMA	1400 bytes
Number of non-cluster head nodes	20 to 45 nodes/cluster

Fig.3.7 shows the average intra-cluster energy consumption as a function of traffic load. A comparison is made for the three schedule based MAC schemes such as TDMA, E-TDMA and BMA protocol with 20 non-cluster head nodes in a cluster and four sessions/round.

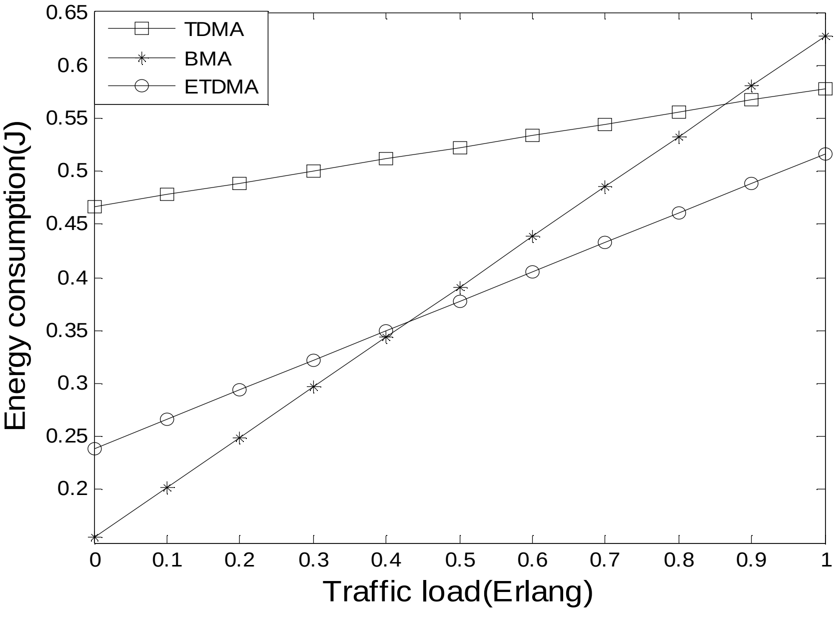

Fig.3.7. Comparison of intra-cluster energy consumed with traffic load

BMA is shown to provide better performance in terms of energy than E-TDMA and TDMA for traffic load lesser than 0.4. The energy consumption of BMA is 15% lesser than that of E-TDMA and is 42% lesser than that of TDMA. This is because BMA protocol avoids idle listening due to dynamic time slot allocations. For traffic load greater than 0.4, the idle period of BMA protocol is small and thus the energy cost from contention period outweighs the energy savings from idle periods. Thus for the traffic loads above 0.4, TDMA scheme performs better.

The performance of TDMA, E-TDMA and BMA protocols in terms of average intra-cluster energy expenditure is shown in Fig.3.8. The analysis is carried out with increasing number of sessions per round with 20 non-cluster head nodes in a cluster and for traffic load 0.3. It is vivid through the results that BMA has better performance when the number of sessions per round is less than four. This is because the sensor nodes forward their data to the cluster head only if significant events occur. It is observed that using BMA protocol there is 12% reduction in energy consumption compared to E-TDMA and 54% reduction in energy consumption compared to TDMA scheme. When the number of sessions is greater than four, the energy consumption of BMA grows because of the increase in contention slots per round.

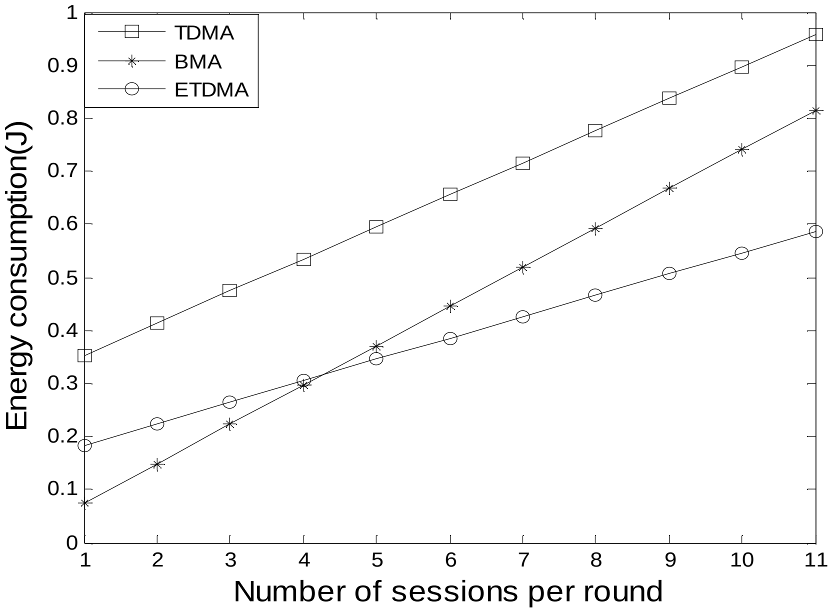

Fig.3.8. Comparison of intra-cluster energy consumption with sessions/round

The average intra-cluster energy consumption with non-cluster head nodes in a cluster for traffic load 0.3 with four sessions per round is shown in

Fig.3.9. When the number of non-cluster head nodes managed by the cluster head node is lesser than 35, BMA protocol performs better than E-TDMA and TDMA schemes. As the number of non-cluster head nodes in the cluster increases, the contention period in BMA increases which results in greater energy consumption. Thus the optimum number of non-cluster head nodes for a cluster adopting BMA scheme is 35.

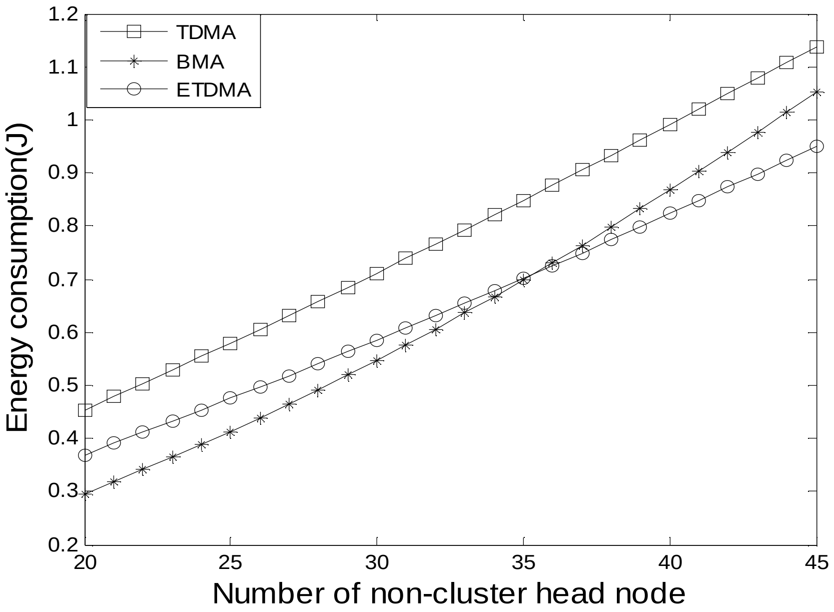

Fig.3.9. Intra-cluster energy consumption with non-cluster head nodes

Fig.3.10 compares the three MAC techniques in terms of average packet delay. For larger traffic load, all the three schemes provide less delay and are almost the same. However as the traffic load decreases, the average packet delay grow exponentially with conventional TDMA and E-TDMA than BMA scheme. This is because in BMA protocol, the scheduling of nodes changes dynamically according to the traffic variations in the network. This greatly reduces the energy consumption of nodes due to idle listening and thus maintains a good and lower delay performance.

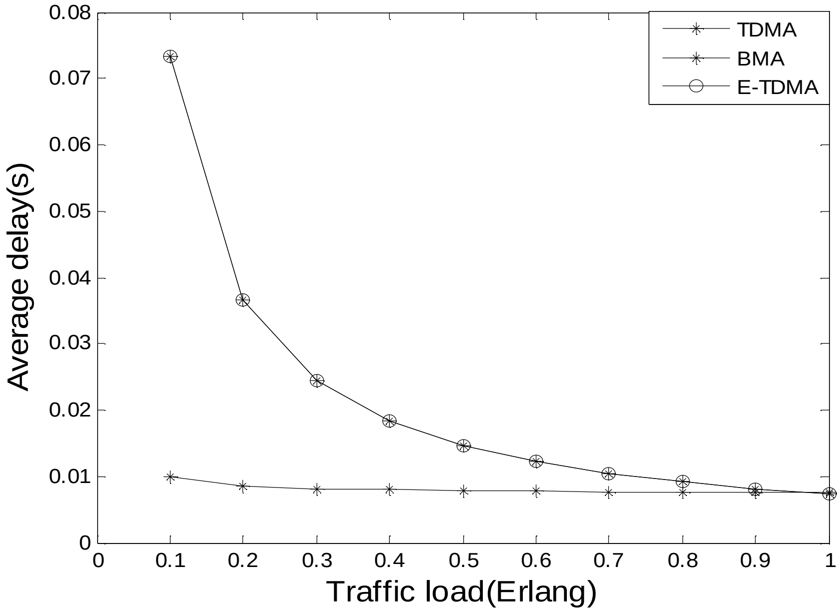

Fig.3.10. Intra-cluster average packet delay

The energy consumption in inter-cluster communication is due to transmission of packets by cluster head nodes to the sink. Fig.3.11 illustrates the energy consumption in transmission of data as a function of traffic load for nanoMAC and np-CSMA scheme.

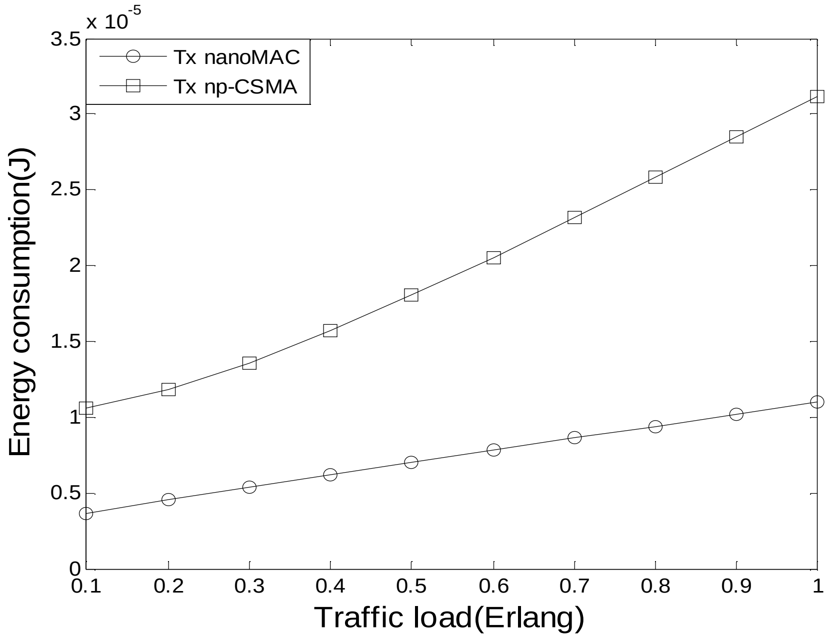

Fig.3.11. Inter-cluster energy consumption with traffic load

The transmission energy consumption of np-CSMA scheme is 65% more than that of nanoMAC. This is because np-CSMA protocol does not use frame train structure and nodes do not sleep during data transmission period and hence its energy consumption on transmission increases very rapidly. NanoMAC on the other hand performs well even in periods of high traffic bursts and its energy consumption stays low by incorporating proper sleep schedules. Thus nanoMAC protocol when used for inter-cluster domain can achieve better energy efficiency.

Fig.3.12 shows the throughput performance comparison of np-CSMA and nanoMAC protocol. When the data frames are 410 bytes, nanoMAC protocol performs better as it sends ten data frames of 41 bytes each instead of one 410 byte data frame and retransmits only the lost frame. It is vivid from the results that nanoMAC outperforms np-CSMA scheme in terms of throughput and is efficient with increasing traffic load.

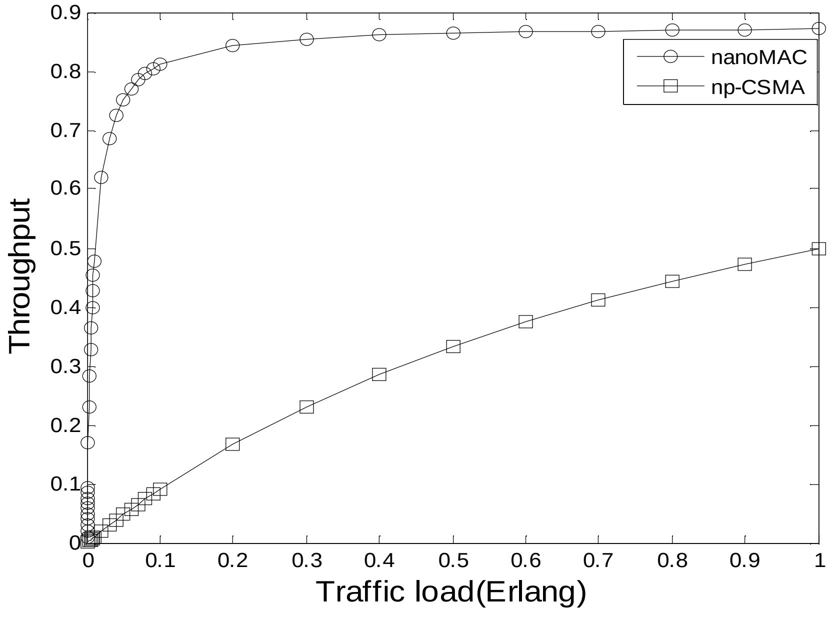

Fig.3.12. Comparison of throughput with traffic load for the inter-cluster

A comparison of normalised delay characteristics of nanoMAC and non-persistent CSMA protocols are shown in Fig.3.13. Using np-CSMA scheme, a device sends a single frame of 410 bytes and their corresponding acknowledgement frames in one transmission period. Upon error or collision during this transmission period, the entire frame has to be retransmitted, hence the delay incurred in reception of frame increases with traffic load. With nanoMAC protocol, a device sends 10 data frames of 41 bytes each for the same transmission period and retransmits only the lost/collided frame, thus the delay offered in the network is reduced compared to non-persistence CSMA.

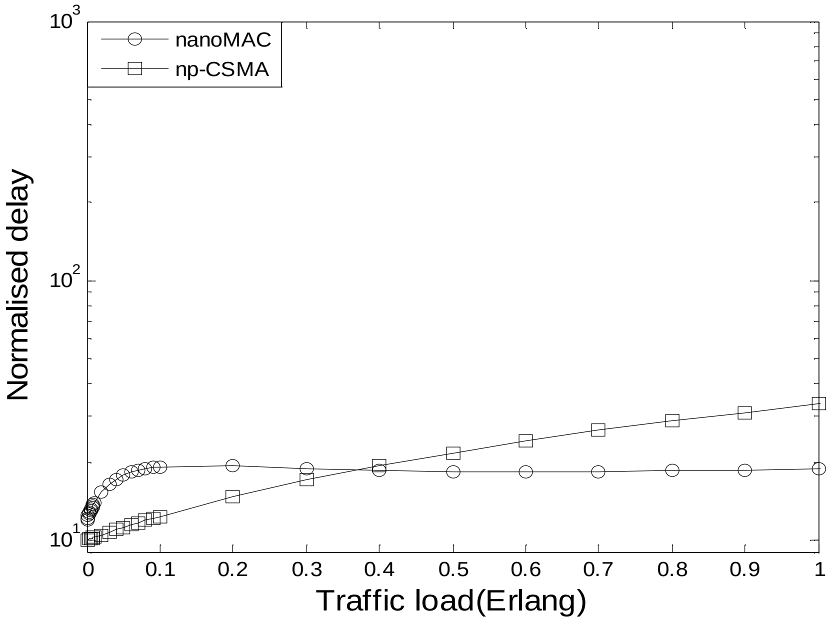

Fig.3.13. Inter-cluster packet delay

Sensor nodes make use of single hop communication between cluster heads and sink. When the distance to reach the destination is increased, multihop communication between the cluster heads and sink is essential to minimise energy consumption [12]. Fig.3.14 shows the energy analysis of np-CSMA and nanoMAC protocol using single hop and multihop communication between cluster head nodes. From the results it is evident that single hop using nanoMAC protocol is the best up to a transmission distance of 100 m (10 hops). As the distance increases above single hop, the energy consumption is increased approximately by a factor of 0.5. Multihop communication using nanoMAC is more attractive and energy efficient when the transmission distance is beyond 100 m (10 hops). Thus nanoMAC protocol can achieve better efficiency when compared to np-CSMA.

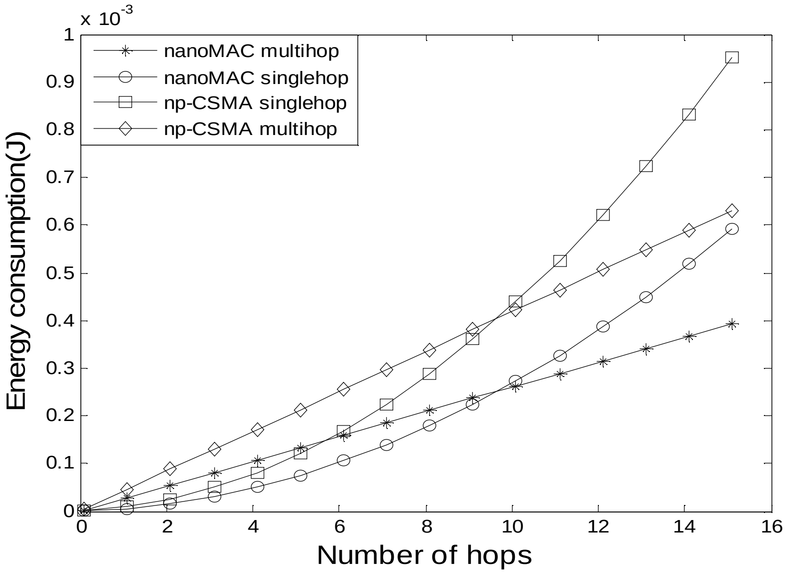

Fig.3.14. Energy consumption of single hop and multihop in inter-cluster domain

Thus the suggested hybrid MAC protocol can significantly reduce energy consumption in the sensor network. BMA MAC protocol when used for intra-cluster domain and nanoMAC protocol when used for inter-cluster domain can achieve higher energy savings when compared to conventional TDMA, E-TDMA and np-CSMA schemes.

3.6 SUMMARY

The performance of the novel hybrid MAC protocol in terms of energy and delay with offered traffic load has been evaluated for the cluster based wireless sensor network. From the simulation results it is evident that for the intra-cluster communication, BMA protocol performs best and achieves 42% reduction in energy consumption compared to TDMA and 15% reduction in energy consumption than E-TDMA scheme and provides 68% lesser packet transmission delay. NanoMAC protocol provides better performance for inter-cluster communication and its energy expended for data transmission is almost 65% lesser than that of np-CSMA protocol. The delay of nanoMAC protocol is considerably reduced without any degradation in throughput when compared with np-CSMA scheme. This reduction in energy consumption and delay of the hybrid MAC protocol can significantly prolong the lifetime of the sensor network.

CHAPTER 4

COOPERATIVE MIMO MAC PROTOCOL

4.1 INTRODUCTION

Sensor network requires robust and efficient communication protocols to minimise delay and save energy. The throughput of WSN can be maximised by selecting an effective medium access control scheme [30] depending on the contention level of the network. However, the lifetime of the network is reduced due to channel fading effects and interference. To enhance the network lifetime, a MIMO MAC scheme is proposed in this chapter for enabling packet transmission utilising space time codes such as STBC [58] and STTC [59] by allowing nodes to transmit and receive information cooperatively. The performance of the proposed cooperative MIMO MAC protocol is evaluated in terms of energy consumption and delay. Simulation results show that the proposed cooperative MIMO MAC protocol utilising space time block code provides reliable and efficient transmission by leveraging MIMO diversity gains.

4.2 MIMO MAC PROTOCOL MODEL

In cooperative MIMO systems, transmit and receive diversity are achieved in a distributed manner by the sending and receiving groups. The cooperative MIMO system model is shown in Fig.4.1. It consists of cooperative sender having multiple sending nodes and receiver having multiple receiving nodes, each with a single antenna. In the sending group, the signals from multiple sending nodes are encoded by space time technique and transmitted to the receiving group. At the receiver, space time decoding is used to separate the received signals and extract the original information.

At the beginning of each data transmission, the source node sends a Recruiting RTS (RRTS) message to its neighbours to solicit help for the transmission of data packet. The RRTS message is transmitted at a power level lower than that for normal transmission to ensure that only the nearby nodes are recruited. The available neighbours will reply with a Sequential CTS (SCTS) message for the purpose of reducing collision with each other [63].

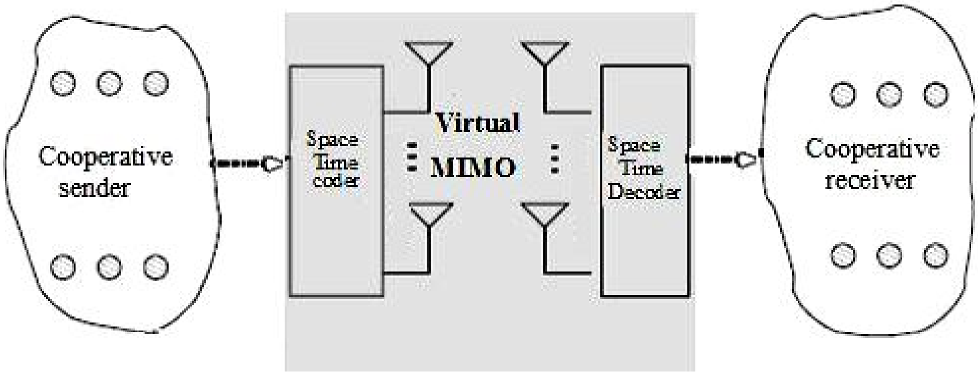

Fig.4.1. Cooperative MIMO system model

After recruiting the sending group, the source node sends a MIMO RTS (MRTS) control message to the destination node to establish data transmission link. The destination node recruits receiving group nodes using the same recruiting procedure as that of source node. After the destination node gets the SCTS reply, it sends broadcast messages to the selected receiving neighbours to recruit them and help in receiving MIMO data from the sending group. The destination node then replies with a MIMO CTS (MCTS) message to source node to confirm the data transmission. If no MCTS is received, the source node times out and retransmits MRTS message to destination node. The flowchart of the cooperative MIMO MAC protocol is shown in Fig.4.2. The cooperative MIMO MAC transmission can be described by the following steps:

i) *Broadcasting*

The source node broadcasts data and synchronisation information with low power to the selected neighbour nodes. The number of cooperative neighbours selected depends on the STC scheme.

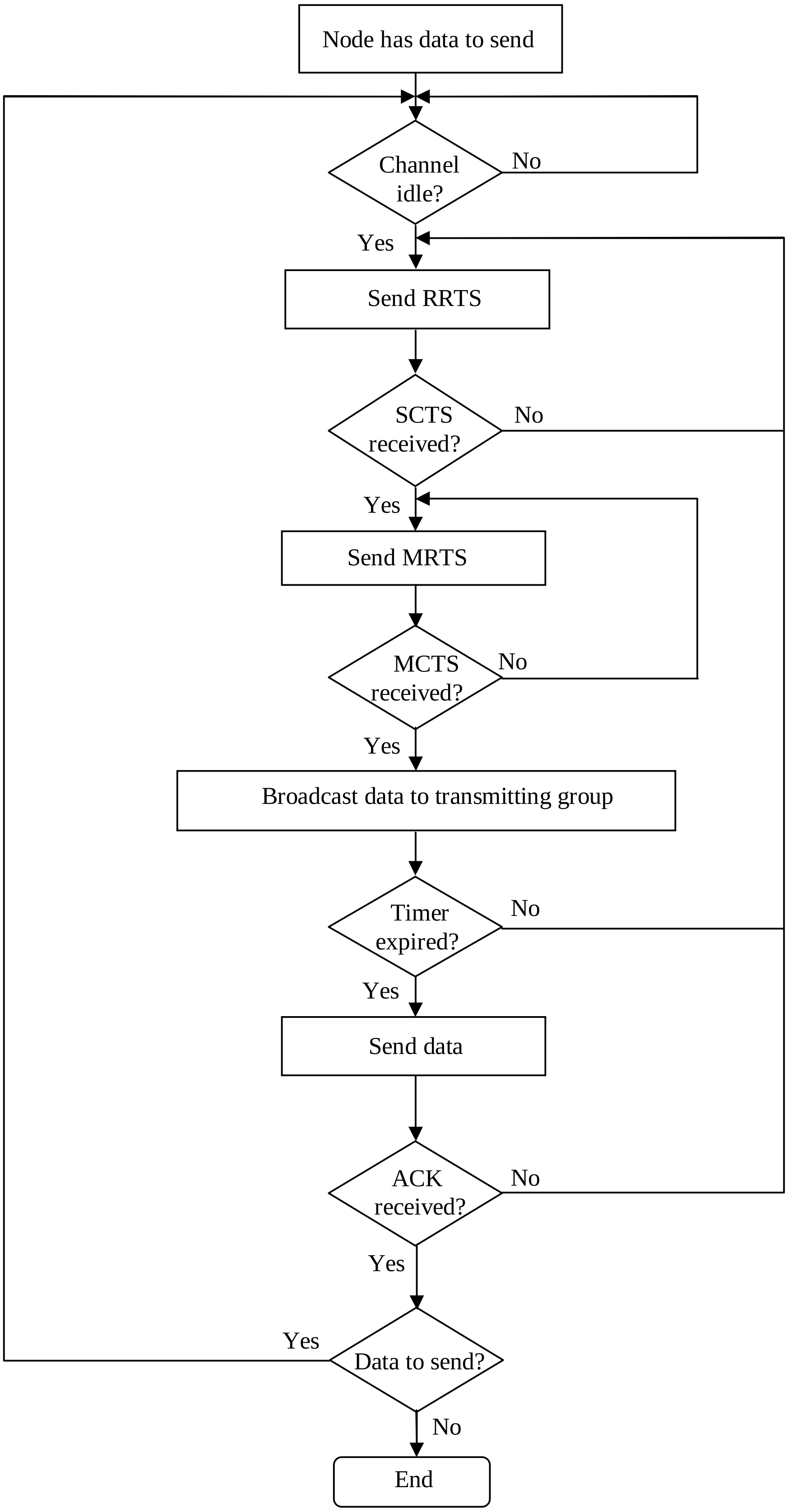

Fig.4.2. Flow chart of cooperative MIMO MAC protocol

The source node also specifies the order for selected neighbour nodes so that each node will choose the corresponding row in space time code matrix for MIMO data transmission [70,71]. Since the distance from the cooperative nodes to source node in the sending group is quite short the members of sending group need not send the acknowledgement back to the source node.

ii) *STC MIMO transmission*

The cooperative nodes in sending group will use the corresponding row in STC code matrix, which is assigned in step1, to change the permutation of data bits. All nodes in the sending group, including the source node, will transmit space time coded data to the receiving group.

iii) *Data collection and combining*

After receiving the data from sending group, each node in the receiving group uses CSI to decode the space time coded data. After decoding STC, the cooperative nodes in receiving group relay their copies to the destination node. The destination receives signal copies from the cooperative nodes and detects them as soft symbols. The destination uses code combining and determines the most possible codeword based on the received soft symbols.

If original data is decoded correctly, the destination node will send back an ACK message to the source node. Otherwise, no ACK is sent and the source nodes will timeout and initiate backoff mechanism before attempting retransmission and the whole procedure is repeated.

4.3 SPACE TIME CODING SCHEME

Space time coding schemes are used to improve the performance of MIMO WSN combating the channel fading and interference. The code provides the full diversity over fading channels and improves the quality of signal transmission.

4.3.1 Space Time Block Code

Space time block code is defined by an ($n_T \times T_{bc}$) transmission matrix Y, where n_T represents the number of transmit cooperative nodes and p represents the number of time periods for transmission of one block of coded symbols [25,49]. The encoder structure of STBC is shown in Fig.4.3. At each encoding operation, a block of m information bits are mapped into the signal constellation (2^m) to select k modulated signals $x_1, x_2, ..., x_k$, where each group of m bits selects a constellation signal. The k modulated signals are then encoded to generate n_T parallel signal sequences according to the STBC transmission matrix Y.

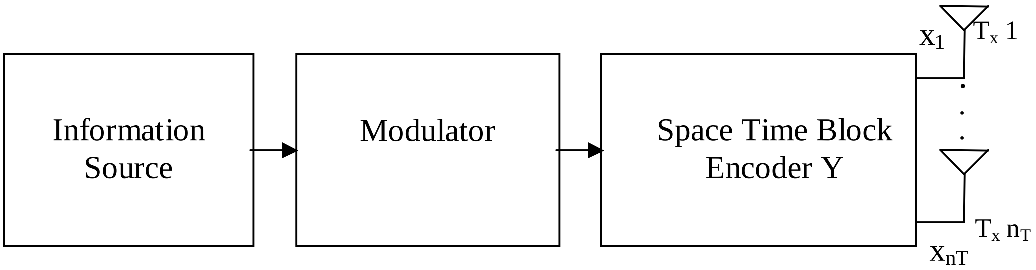

Fig.4.3. Encoder for STBC

The i^{th} row of transmission matrix Y represents the symbols transmitted from the i^{th} transmit cooperative node consecutively in T_{bc} transmission periods, while the j^{th} column of Y represents the symbols transmitted simultaneously through n_T transmit cooperative nodes at time j. The element of Y in the i^{th} row and j^{th} column, $x_{i,j}$, (where $i=1,2,\ldots,n_T$, $j=1,2,\ldots, T_{bc}$) represents the signal transmitted from the cooperative node i at time j.

In case of n_T =2, 3 transmit cooperative nodes, the STBC transmission matrix Y_2, Y_3 are used [49,58,60] and are defined by

$$Y_2^* = \begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{pmatrix} \tag{4.1}$$

$$Y_3^* = \begin{pmatrix} x_1 & -x_2 & -x_3 & -x_4 & x_1^* & -x_2^* & -x_3^* & -x_4^* \\ x_2 & x_1 & x_4 & -x_3 & x_2^* & x_1^* & x_4^* & -x_3^* \\ x_3 & -x_4 & x_1 & x_2 & x_3^* & -x_4^* & x_1^* & x_2^* \end{pmatrix} \tag{4.2}$$

where $[.]^*$ denotes the complex conjugate operation.

The entries of the transmission matrix Y are linear combinations of the k modulated symbols $x_1, x_2, ..., x_k$ and their conjugates $x_1^*, x_2^*, ..., x_k^*$. In order to achieve the full transmit diversity of n_T, the transmission matrix Y is constructed based on orthogonal designs such that

$$Y.Y^H = a(|x_1|^2 + |x_2|^2 + ... + |x_k|^2)I_{nT} \tag{4.3}$$

where Y^H is the Hermitian of Y
a is the constant
I_{nT} is an(n_T x n_T) identity matrix

When $\mathbf{x}_i$ = ($x_{i,1}$,$x_{i,2}$,...,$x_{i,\ Tbc}$) is the transmitted sequence from the i^th cooperative node and $\mathbf{x}_j$ = ($x_{j,1}$,$x_{j,2}$,…,$x_{j,\ Tbc}$) is the transmitted sequence from the j^th cooperative node, the inner product of the sequences $\mathbf{x}_i$ and $\mathbf{x}_j$ is represented as

$$\mathbf{x}_i \cdot \mathbf{x}_j = \sum_{t=1}^{T_{bc}} x_{i,t}.x_{j,t}^* = 0, \quad i \neq j, \quad i, j \in \{1,2,...,n_T\} \tag{4.4}$$

The inner product of the sequences enables the orthogonality for a given number of transmit cooperative nodes. In addition, it allows the receiver to decouple the signals transmitted using a simple maximum likelihood decoder [49]. The receiver estimates the transmitted signal x_i and the decision statistics obtained at the decoder is given by

$$\overline{x_i} = \sum_{t=1}^{n_T}\sum_{j=1}^{n_R} \mathrm{sgn}_t(i).\, r_t^j .\, h_{j,\in_t(i)}^* \tag{4.5}$$

where n_R represents the number of receiving cooperative nodes

$sgn_t(i)$ is the sign of x_i in the t^{th} column

r_t^j is the received signal at cooperative node j at time t

h is the fading attenuation coefficient for the path from transmit cooperative node i to receive cooperative node j at time t

$\in_t(i)$ is the permutation of symbols from first column to the t^{th} column in row position, x_i

4.3.2 Space Time Trellis Code

The encoder structure of space time trellis coded Quadrature Phase Shift Keying (QPSK) modulation [49] with n_T transmit cooperative nodes is shown in Fig.4.4. The m binary input sequences $\mathbf{c}^1,\mathbf{c}^2,\ldots,\mathbf{c}^m$ are fed into the encoder, which consists of m feed forward shift registers.

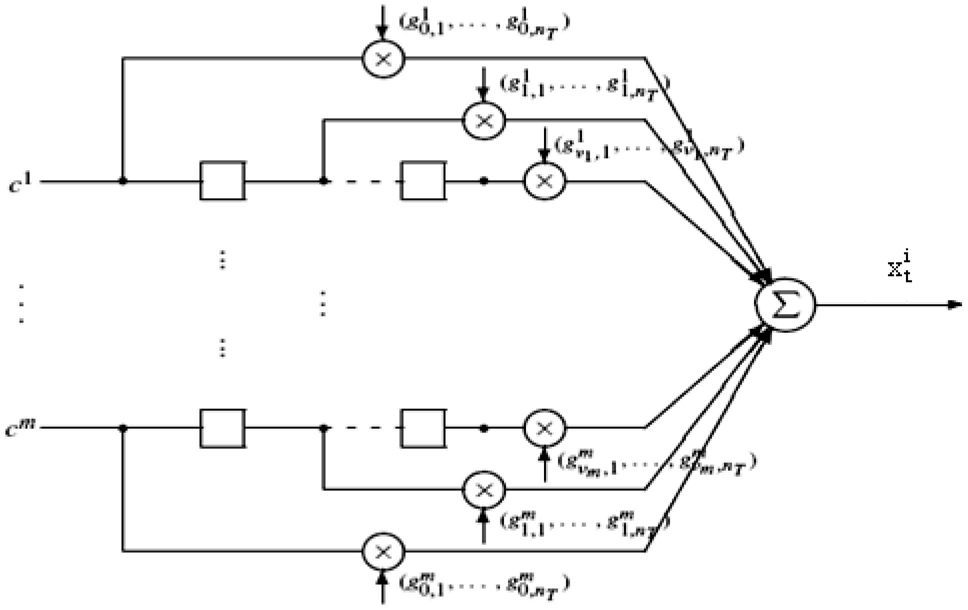

Fig.4.4. Encoder for STTC

The k^{th} input sequence, $\mathbf{c}^k$ fed to the encoder is given by

$$\mathbf{c}^k = (c_0^k, c_1^k, c_2^k, \ldots, c_t^k, \ldots), \quad k=1,2,\ldots,m \tag{4.6}$$

The sequence is passed to the kth shift register and is multiplied by an encoder coefficient set. The connections between the shift register elements and the modulo 4 adder is described by m multiplication coefficient set sequences and is given by

$$g^1 = [(g^1_{0,1}, g^1_{0,2}, ..., g^1_{0,nT}), (g^1_{1,1}, g^1_{1,2}, ..., g^1_{1,nT}), ..., (g^1_{v1,1}, g^1_{v1,2}, ..., g^1_{v1,nT})]$$

$$g^2 = [(g^2_{0,1}, g^2_{0,2}, ..., g^2_{0,nT}), (g^2_{1,1}, g^2_{1,2}, ..., g^2_{1,nT}), ..., (g^2_{v2,1}, g^2_{v2,2}, ..., g^2_{v2,nT})]$$

$$\begin{array}{ccc} . & . & . \\ . & . & . \\ . & . & . \end{array}$$

$$g^m = [(g^m_{0,1}, g^m_{0,2}, ..., g^m_{0,nT}), (g^m_{1,1}, g^m_{1,2}, ..., g^m_{1,nT}), ..., (g^m_{vm,1}, g^m_{vm,2}, ..., g^m_{vm,nT})] \quad (4.7)$$

where $g^k_{j,i}$, is an element of the QPSK constellation set

$i=1,2,\ldots,n_T$

$j=1,2,\ldots,\nu_k$

ν_k is the memory order of the kth shift register

The encoder maps binary data to modulation symbols, where the mapping function is described by a trellis diagram as illustrated in Fig.4.5. In this figure, the state bits are shown at the right of the trellis with each line representing a possible transition with the input bits shown beside the lines. The output of the current state is shown at the left of the trellis [26,27,49].

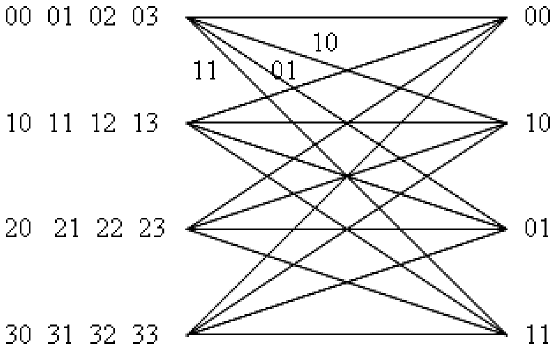

Fig.4.5. Trellis diagram for STTC

The encoder output at time t for transmit cooperative node i, denoted by x_t^i, can be computed as

$$x_t^i = \sum_{k=1}^{m} \sum_{j=0}^{v_k} g_{j,i}^k \, c_{t-j}^k \mod 4, \quad i=1,2,\ldots,n_T \tag{4.8}$$

The STTC decoder employs the Viterbi algorithm to perform maximum likelihood decoding [59,60]. Assuming that perfect CSI is available at the receiver, the branch metric is computed as squared Euclidean distance between the hypothesized received symbols and actual received signals as

$$Y_t = \sum_{j=1}^{n_R} \left| r_t^j - \sum_{i=1}^{n_T} h_{j,i}^t \, x_t^i \right|^2 \tag{4.9}$$

The Viterbi algorithm selects the path with the minimum path metric as the decoded sequence.

4.4 ANALYSIS OF COOPERATIVE MIMO MAC PROTOCOL

A mathematical model to evaluate the performance parameters such as, error probability, energy consumption and packet delay for the proposed cooperative MIMO MAC protocol is described below. The bit error probability is used to analyse the system energy consumption and delay incurred in the transmission of data from source to destination.

4.4.1 Bit Error Probability

The bit error performance of the cooperative MIMO system is evaluated taking into account that the system transmits QPSK signals through Rayleigh fading channel with additive white Gaussian noise [71]. The relationship between the packet error probability p_p and bit error probability p_e for the frame length of L bits is given by

$$p_p = 1-(1-p_e)^L \tag{4.10}$$

Data transmission errors are generated from two factors in cooperative MIMO i.e., from the sending to receiving group and from cooperative receiving nodes to destination. Thus the bit error performance for the transmission of data from transmit cooperative node to receive cooperative node and the performance for data collection at the destination is considered for analysis.

4.4.2 Energy Consumption Analysis

Consider a scenario with n_T senders and n_R receivers involved in cooperative MIMO transmission. The energy consumed for an unsuccessful transmission attempt and for a successful transmission from sending to the receiving group using STBC and STTC MIMO MAC are calculated to analyse the overall energy consumption in a hop [67,68, 70,71]. The energy consumption for an unsuccessful transmission attempt is

$$\begin{aligned} Eu_{coop} &= E_{mrts} + E_{mcts} + 2E_{rrts} + (n_T - 1)E_{scts} \\ &\quad + (n_R - 1)E_{scts} + E_{bs} + E_{data} + (n_R - 1)E_{col} \end{aligned} \tag{4.11}$$

and the energy consumption for a successful attempt is

$$\begin{aligned} Es_{coop} &= E_{mrts} + E_{mcts} + 2E_{rrts} + (n_T - 1)E_{scts} + (n_R - 1)E_{scts} \\ &\quad + E_{bs} + E_{data} + (n_R - 1)E_{col} + E_{ack} \end{aligned} \tag{4.12}$$

where E_{mrts} is the energy consumed in sending MIMO RTS

E_{mcts} is the energy consumed in sending MIMO CTS

E_{rrts} is the energy consumed in sending RRTS

E_{scts} is the energy consumed in sending SCTS

E_{bs} is the energy spent by the source node to send the data

E_{data} is the energy consumption for data transmission between sending and receiving group

E_{col} is the energy consumed by destination or sink node to collect the data from cooperative receiving group

E_{ack} is the energy consumed in sending ACK

The MRTS and MCTS messages are control messages between source and destination and they require higher transmission power for long distance transmission. The RRTS and SCTS are control messages between source/destination and their neighbours. Compared to the MIMO RTS and CTS, RRTS and SCTS messages are transmitted with less power due to shorter distance of transmission. In the receiving group, each node will transmit its signal back to the destination with energy E_{col} and there are $(n_R - 1)$ cooperative nodes in the receiving group, excluding the destination node.

The total energy consumption for one-hop transmission in cooperative MIMO system is given by

$$E_M = \frac{p_p}{(1 - p_p)} Eu_{coop} + Es_{coop} \tag{4.13}$$

4.4.3 Packet Transmission Delay

Each packet transmission in cooperative MIMO requires more steps as shown in Fig.4.2 which may increase the packet delays. However, the reduction in the packet error probability with cooperative MIMO MAC reduces the occurrence of retransmissions which in turn reduces the packet delays. The duration of transmission attempt [63] that is successful using cooperative MIMO transmission is given by

$$Ts_{coop} = T_{rts} + T_{Br} + T_{cts} + T_{Bs} + T_{data} + T_{col} + T_{ack} \tag{4.14}$$

and the duration for an unsuccessful attempt is

$$Tu_{coop} = T_{rts} + T_{Br} + T_{cts} + T_{Bs} + T_{data} + T_{col} + T_{wait} \tag{4.15}$$

where T_{rts} is the transmission time for the RTS

T_{Br} is the transmission time of a recruitment message sent by the destination node

T_{cts} is the transmission time for the CTS

T_{Bs} is the transmission time required for the source node to send the data packet to its cooperating nodes

T_{data} is the transmission time for the data

T_{col} is the time required by the cooperating receiving nodes to send the data to the destination

T_{ack} is the transmission time for the ACK

T_{wait} is the duration for which sender waits for an ACK

The total expected packet delay for cooperative MIMO MAC is given by

$$\tau_d = \frac{p_p}{(1-p_p)} Tu_{coop} + Ts_{coop} \tag{4.16}$$

4.5 RESULTS AND DISCUSSION

The performance of cooperative MIMO MAC protocol with STBC, STTC and uncoded schemes are evaluated in terms of energy consumption and delay for transmission of data packets from source to the destination node using MATLAB 7. The parameters considered for simulation [63,70,71] is summarised in Table 4.1.

Table 4.1 Simulation parameters for MIMO MAC protocol

Parameter	Value
Time for transmitting RTS	36 ms
Time for transmitting CTS	31 ms
Time for transmitting ACK	32 ms
Time for transmitting data	0.006 s
Energy consumed for transmission of RTS, CTS and ACK	0.027J
Energy consumed for transmission of data	0.2J
Modulation type	QPSK

4.5.1 Energy Analysis of Cooperative MIMO MAC with Uncoded Scheme

The energy consumption for various diversity orders (2x2, 3x3 and 4x4) with the uncoded system for the proposed MAC protocol is shown in Fig.4.6. For lesser cooperative sending and receiving group sizes, Symbol Error Rate (SER) increases at low SNR, which in turn results in multiple retransmissions, thereby resulting in higher energy consumption of sensor node. As the SNR increases, reduction in SER decreases energy consumption. The energy consumption is lesser when 4x4 cooperative nodes are used at transmit and receive clusters. This reduction in energy consumption is due to higher diversity gain of cooperative MIMO systems.

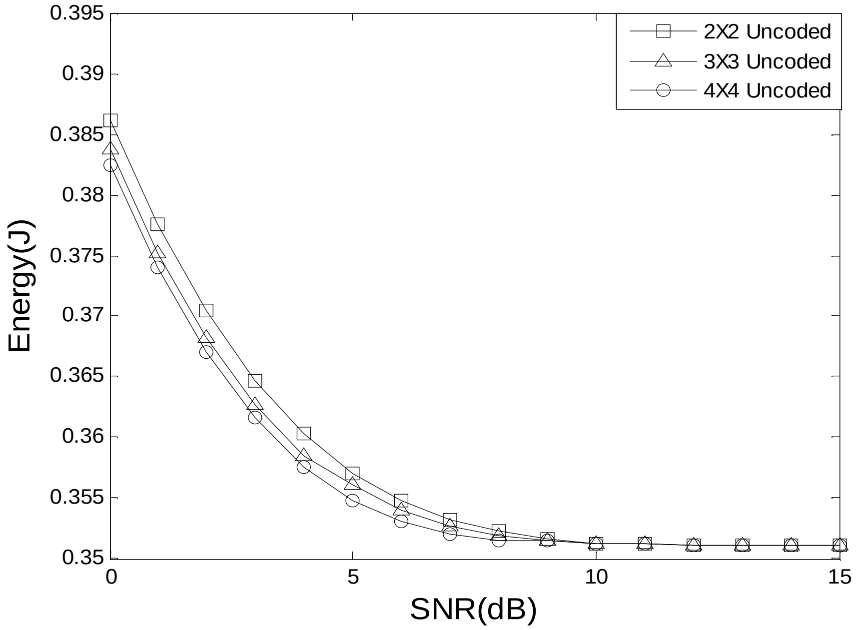

Fig.4.6. Energy analysis of uncoded scheme

4.5.2 Energy Analysis of Cooperative MIMO MAC with STBC Scheme

The energy consumption of various diversity orders (2×2, 3×3 and 4×4) are presented for the STBC scheme in Fig.4.7. When comparing the performance of the STBC with the uncoded scheme shown in Fig.4.6 it is observed that there is a significant reduction in energy consumption because of diversity gain of coded MIMO system. The energy consumption with 4×4 diversity order is 16% lesser than that of 2×2 MIMO configuration. The increase in cooperative group size does not improve the system performance to great extent as smaller improvement of performance is noticed when the system uses 3×3 and 4×4 cooperative sending and receiving group size. Moreover, the maximum number of cooperative nodes used for simulation is restricted to four as further increase of it introduces hardware complexity and cost of the system.

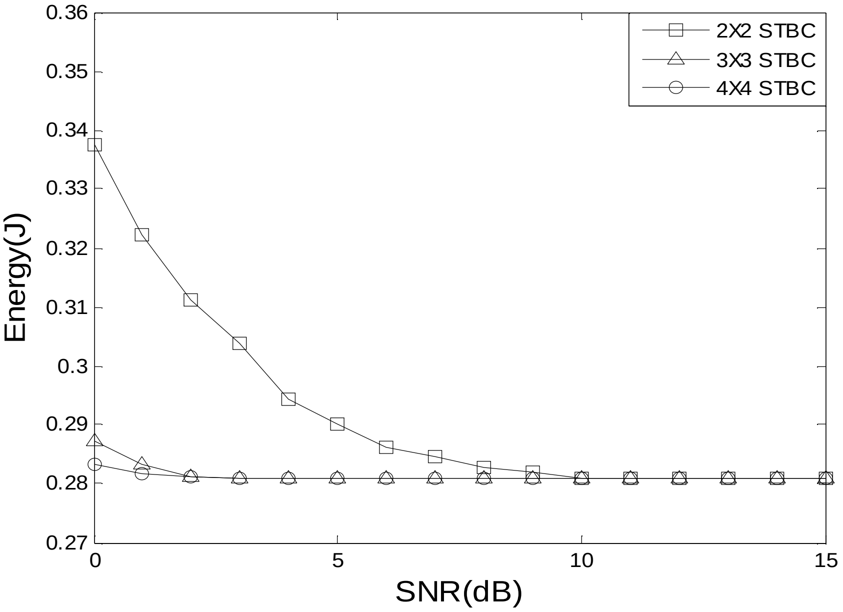

Fig.4.7. Energy analysis of STBC scheme

4.5.3 Energy Analysis of Cooperative MIMO MAC with STTC Scheme

The energy consumption of different cooperative nodes (2×2, 3×3 and 4×4) at transmit and receive cluster using STTC scheme is evaluated in Fig.4.8.

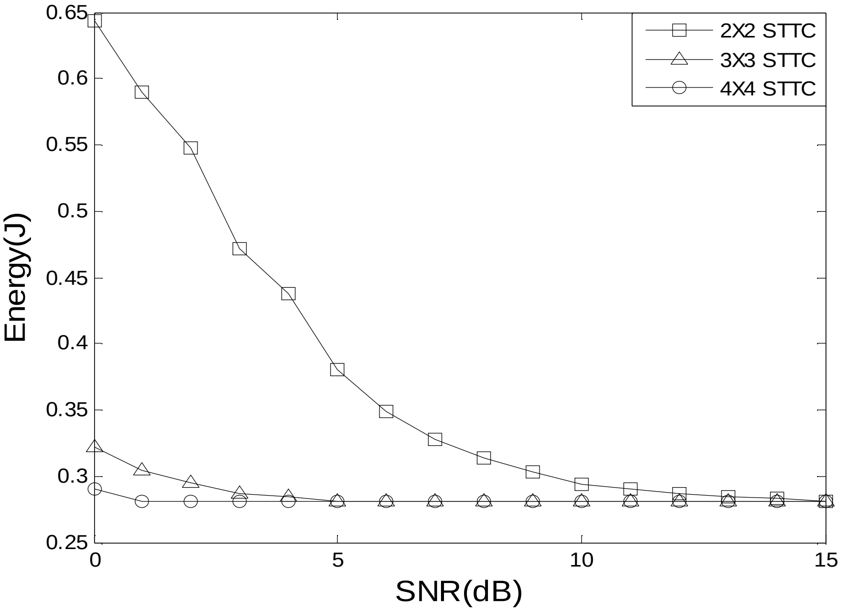

Fig.4.8. Energy analysis of STTC scheme

The energy characteristics obtained are similar to that of STBC cooperative MIMO MAC protocol. The 2×2 MIMO configuration consumes 50% and 54% more energy compared to 3×3 and 4×4 MIMO system respectively. Irrespective of the coding technique used the improvement in energy consumption is noticed clearly with increase in cooperative sending and receiving group sizes. This is due to the diversity gain of coding schemes. When evaluating the performance of STTC with STBC scheme shown in Fig.4.7, the energy performance of STTC degrades to smaller extent as it introduces additional hardware complexity in decoding.

4.5.4 Delay Analysis of Cooperative MIMO MAC with Uncoded Scheme

The delay incurred for various transmit and receive group sizes (2×2, 3×3 and 4×4) are plotted in Fig.4.9 using uncoded scheme.

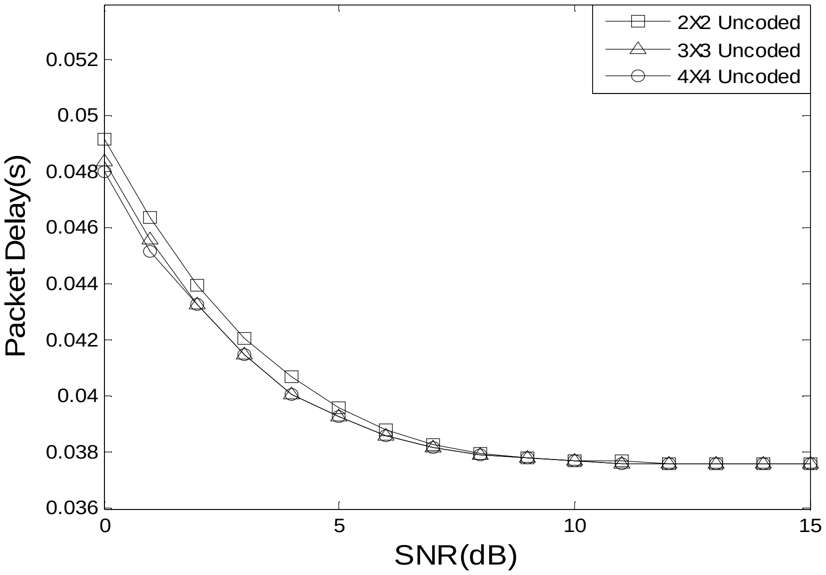

Fig.4.9. Delay analysis of uncoded scheme

The packet delay keeps decreasing at low SNR with the increase in the number of receiving cooperative nodes. The decrease in delay is due to lesser SER and fewer retransmissions in the system. It is clear that for the proposed scheme, the cooperative group size 4×4 has fewer data retransmissions and results in 2% lesser packet latency than 2×2 system.

4.5.5 Delay Analysis of Cooperative MIMO MAC with STBC Scheme

The delay performance with STBC scheme for various transmit and receive group sizes (2×2, 3×3 and 4×4) are portrayed in the Fig.4.10. The delay keeps reducing with the increase in the diversity order due to fewer packet retransmissions. It is vivid from the figure that the STBC based cooperative MIMO MAC scheme with diversity order of 2×2 incurs a increase in delay of about 67% and 80% over 3×3 and 4×4 MIMO system repectively.

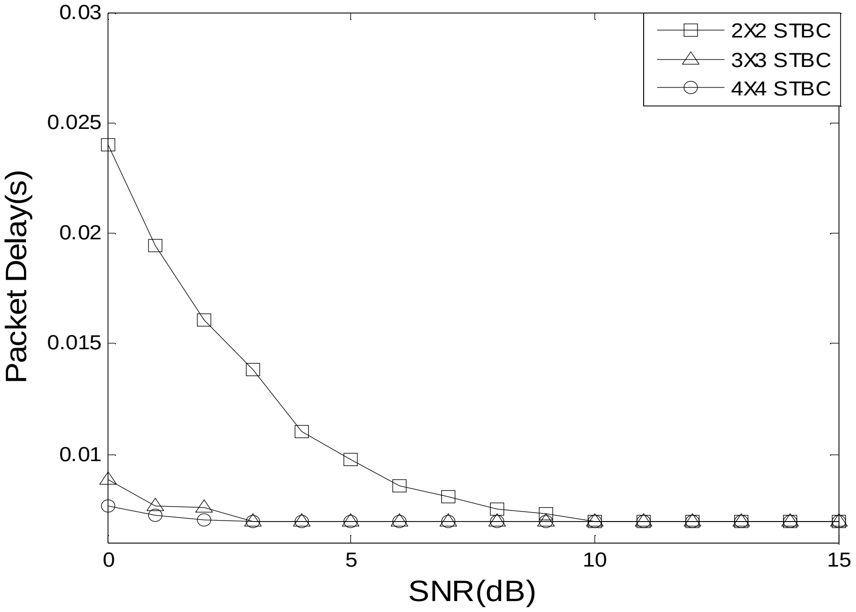

Fig.4.10. Delay analysis of STBC scheme

4.5.6 Delay Analysis of Cooperative MIMO MAC with STTC Scheme

The delay analysis of STTC based cooperative MIMO MAC protocol for various orders of diversity (2×2, 3×3 and 4×4) is illustrated in Fig.4.11 which is similar to Fig.4.10.

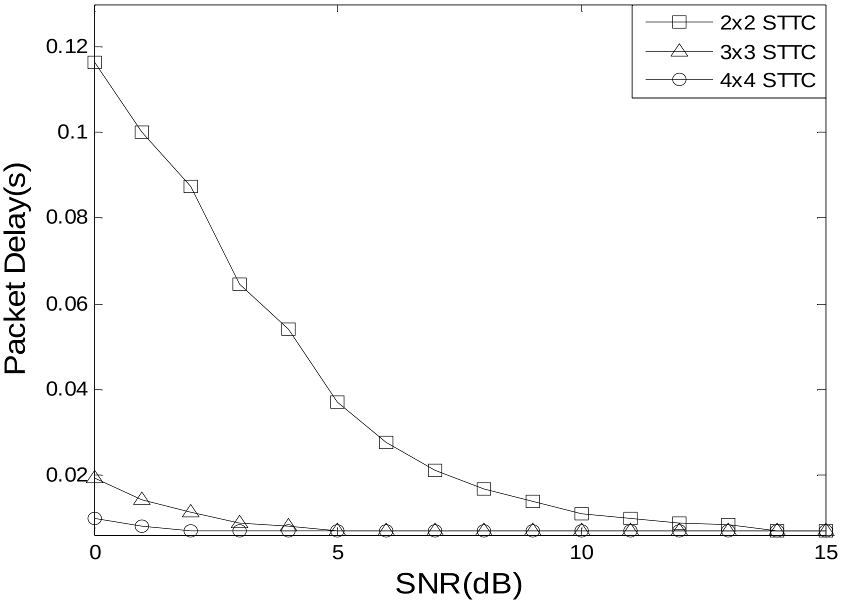

Fig.4.11. Delay analysis of STTC scheme

The delay incurred in the transmission of data reduces with the increase in the number of cooperative nodes both at transmitter and receiver clusters by exploiting coding and diversity gain. It is evident from the results (Fig.4.11) that 2×2 STTC based cooperative MIMO MAC scheme incurs larger delay of about 83% and 96% over 3×3 and 4×4 MIMO system respectively.

4.5.7 Energy Analysis Comparison of Cooperative MIMO MAC with STBC, STTC and Uncoded Scheme

Fig.4.12 demonstrates the energy comparison of the 4x4 MIMO system with STBC, STTC and uncoded schemes. In coded scheme the number of packet retransmissions decreases and results in lesser energy consumption. It is obvious that STTC offers 24% lesser energy consumption and STBC consumes lesser energy by an amount of 26% than uncoded scheme. This is due to the fact that STBC provides better diversity gain and lesser hardware complexity than STTC scheme.

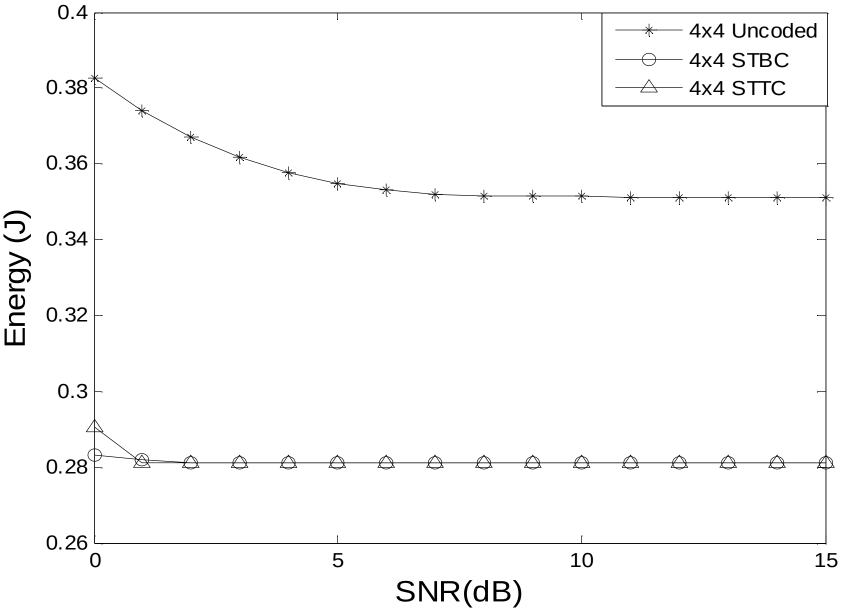

Fig.4.12. Energy analysis comparison of 4x4 cooperative group size for STBC, STTC coding and uncoded scheme

4.5.8 Delay Analysis Comparison of Cooperative MIMO MAC with STBC, STTC and Uncoded Scheme

The delay incurred by the cooperative MIMO MAC protocol is due to transmission of RTS, CTS, ACK and data between the sending and receiving group. Fig.4.13 illustrates the delay responses of a 4x4 cooperative MIMO configuration for STBC, STTC and uncoded schemes. It is vivid that STBC offers better performance in terms of delay over STTC scheme by providing better diversity gain for transmission of data packets from the source to destination cluster.

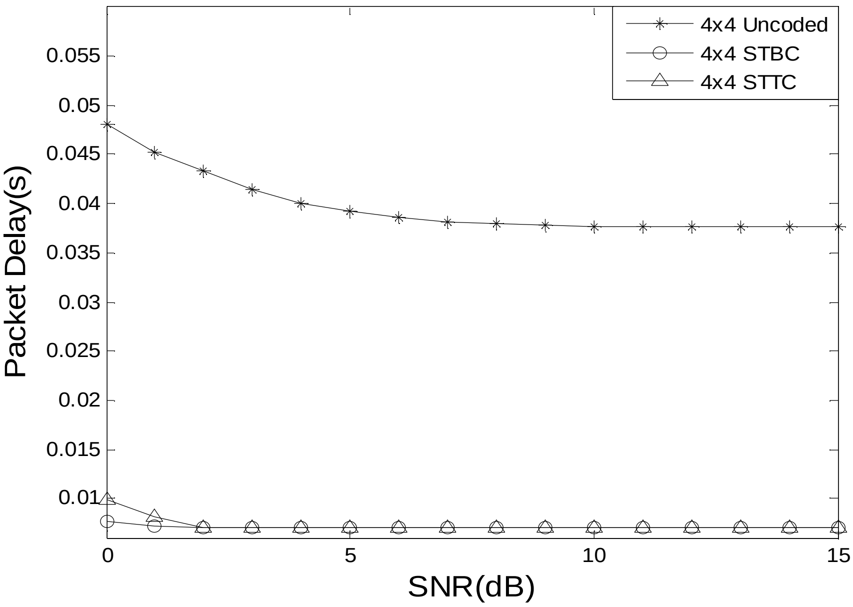

Fig.4.13. Delay analysis comparison of 4x4 cooperative group size for STBC, STTC coding and uncoded scheme

4.6 SUMMARY

A MAC protocol utilising cooperative MIMO transmission in wireless sensor network has been explored to maximise the network lifetime. The performance of the cooperative MIMO MAC system is evaluated for various orders of diversity (2×2, 3×3 and 4×4) with uncoded scheme and STC and in terms of energy and delay. Simulation results prove that 4×4 MIMO configuration with space time block code performs better and consume lesser energy and delay for packet transmission than uncoded scheme and STTC. This results from the reduction in SER and diversity gain of higher order MIMO configurations.

CHAPTER 5

THRESHOLD BASED MAC PROTOCOL

5.1 INTRODUCTION

Cooperative multi input multi output schemes can combat the fading effects in wireless sensor network and can significantly improve the communication performance. The traffic offered to the sensor network is highly dynamic and the MAC protocol devised may diminish the performance gains of MIMO operation. To maintain stability under higher traffic loads, a distributed threshold based MAC protocol [72,107] for cooperative MIMO transmissions using space time codes [49,59] is proposed in this chapter. The propounded threshold based MAC scheme dynamically updates and selects the cooperative group size based on the queue length at the sending node. STC techniques are applied for MIMO data transmission to utilise the inherent spatial diversity in wireless systems. Simulations are provided to evaluate the performance of the proposed MAC protocol with STC coding and uncoded scheme in terms of energy and delay.

5.2 PROPOSED COOPERATIVE MIMO MAC PROTOCOL

The proposed cooperative MIMO MAC protocol for coordinating transmissions from multiple nodes is discussed below. When a node has data to send, it first senses the channel to ensure that it is idle. If the channel is sensed to be busy, the node initialises a backoff timer in the range $[1,CW_{min}]$ and waits for the idle channel. The timer is decremented once the channel is sensed idle and interrupted if the channel becomes busy again. If the channel is idle and the backoff timer has decremented to zero, the source node broadcasts a recruiting message at low transmission power to its local neighbours for cooperative transmission [70,71].

When the replies are received from the neighbours, the source node transmits a RTS message to destination at normal power. The RTS message contains information on the current queue length at the sender and the number of neighbours it has recruited. This information is used by the receiver to update the cooperative threshold. It then waits for the CTS reply from destination node to reserve the channel for data transmission.

When the source does not receive a CTS packet within the specified time interval, the node automatically attempts for retransmission. If the source node receives a Negative CTS (NCTS) packet from the destination node, it will backoff and attempt for retransmission and the receiver is unable to update the cooperative threshold.

Once a CTS packet is received, the source node proceeds with the data transmission. Each CTS packet contains the optimum size of the cooperative group at the sending end. The source node broadcasts the data packet at low power to the nodes in its group and synchronises them. Each node in the source cluster transmits the data cooperatively using STC coding and waits for an ACK from the destination node.

The destination node on receiving the RTS packet, seeks for an idle channel. If the channel is idle, the destination node sends a recruiting packet at low power to recruit its neighbours. On receiving replies from nodes willing to cooperate for reception, the destination node uses the information in the RTS packet to calculate the threshold. The determination of cooperative threshold is described in section 5.3.

If the channel's estimated BER is higher than the cooperative threshold value, a NCTS packet is sent to source node to cancel the transmission. On the other hand, if the threshold is met, the destination node broadcasts a low power message to the cooperative receiving group to help in the reception. It then sends a CTS packet with the required cooperative group size to source node and waits for the data packet.

Each node in the destination cluster sequentially forwards its copy of the received data packet to the destination node. Finally, the destination node decodes the packet by combining all copies of the received packet and replies with an ACK packet to the source if the packet is decoded correctly. Otherwise, the destination node does nothing and the source node eventually times out.

5.3 PROPOSED THRESHOLD SCHEME

The destination node uses the RTS information i.e., queue length and available cooperative node at the sender to calculate the threshold. The methodology to determine the threshold for the proposed MAC protocol is shown in Fig.5.1. Consider the maximum number of nodes available for cooperation with the source and destination nodes as n_T and n_R respectively. The expected bit error probability, $p_e(n_T,n_R)$ is first evaluated using STC coding to determine the cooperative threshold.

The number of unique values of $p_e(n_T,n_R)$ obtained is denoted by K. The successful transmission probability for each value of K is obtained by subtracting $p_e(n_T,n_R)$ from one. The successful transmission probabilities are listed in order $\varphi(1)$, $\varphi(2),\ldots,\varphi(K)$. Let $\varphi(i)$ be defined as the mapping of $i \rightarrow (n_T, n_R)$ from successful transmission probability i.e., $1-p_e(n_T,n_R)$ to the cluster size (n_T, n_R) and is given by

$$\phi(\mathrm{i}) = \{(n_T, n_R) \,|\, 1 - p_e(n_T, n_R)\} \tag{5.1}$$

When the current queue length at the sender is Q, threshold i, (i.e., $\varphi(i)$ in terms of the desired successful transmission probability) is chosen if $(K-i)\xi < Q \leq (K-i+1)\xi$, where ξ is a fixed positive integer. The threshold is set at 1 for $Q > K\xi$. For threshold i chosen, the possible set of $S = (n_T, n_R)$ cluster sizes is obtained for which the packet delivery rate is greater than $\varphi(i)$.

The destination node does an exhaustive search of the possible group sizes of n_T, n_R of φ(i) and selects the combination that has the lowest energy consumption subject to the threshold. The cooperative group size (n_T, n_R) corresponding to this energy consumption is dynamically selected as sending and receiving group for data transmission.

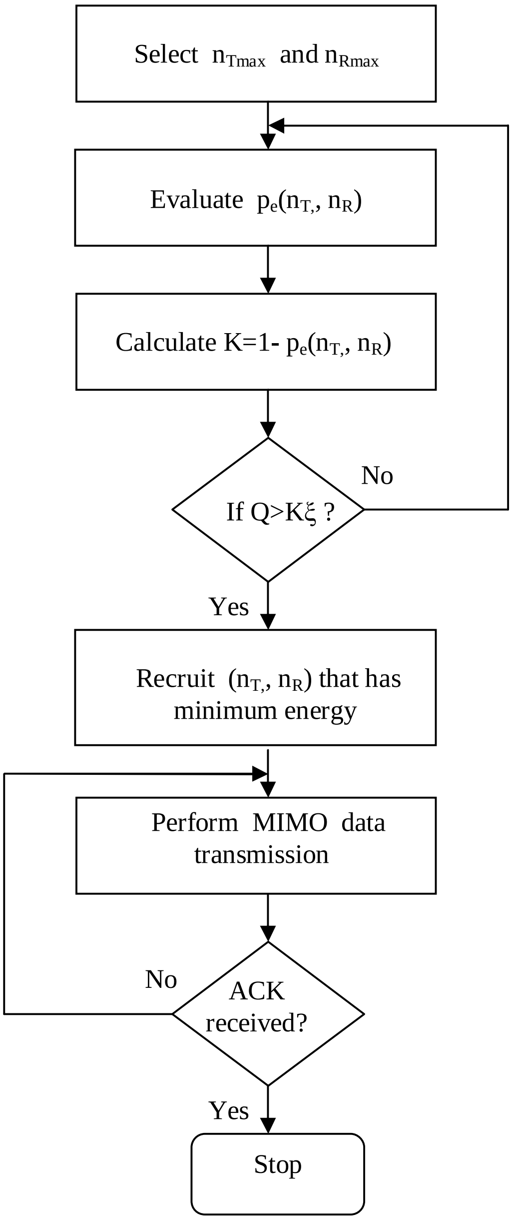

Fig.5.1 Flow chart of threshold scheme for the proposed MAC protocol

5.4 ANALYSIS OF THRESHOLD BASED COOPERATIVE MIMO MAC PROTOCOL

5.4.1 Energy Consumption Analysis

Consider n_T senders and n_R receivers involved in cooperative MIMO transmission. The energy consumed for each transmission can be divided into two parts: the energy spent on channel recruiting and the energy spent on data transmission [107]. The energy spent waiting for RTS/CTS exchange as well as the recruitment process is given by

$$E_{wait} = E_{rts} + E_{cts} + E_{recruit} \tag{5.2}$$

where E_{rts} is the energy consumed in sending RTS packet

E_{cts} is the energy consumed in sending CTS packet

$E_{recruit}$ is the energy consumed on recruiting neighbouring nodes

When the neighbouring nodes reply to the recruiting messages, the recruiting energies of source and destination E_{rec_s} and E_{rec_d} respectively, is given by

$$E_{recruit} = 2E_{rec\_s} + (n_T + n_R)E_{rec\_d} \tag{5.3}$$

The energy consumed for an unsuccessful and successful transmission using MIMO MAC is calculated to analyse the overall energy consumption in a hop. The energy consumption for an unsuccessful transmission attempt is

$$Eu_{coop} = E_{wait} + E_{br} + E_{bs} + n_T E_{data} + (n_R - 1)E_{col} \tag{5.4}$$

and the energy consumption for a successful transmission attempt is

$$Es_{coop} = E_{wait} + E_{br} + E_{bs} + n_T E_{data} + (n_R - 1)E_{col} + E_{ack} \tag{5.5}$$

where E_{bs} is the energy spent by the source node to send the data to its cooperative neighbours

The total energy consumption for one-hop data transmission in cooperative MIMO system depends on the chosen threshold i or φ(i) and is calculated using the equation (4.13).

With the given number of nodes available at the sending and receiving groups, the destination node does an exhaustive search of the possible cooperative group sizes of n_T, n_R and selects the combination that has lower energy consumption, subject to the threshold for MIMO data transmission.

5.4.2 Packet Transmission Delay

Using the threshold based cooperative MIMO MAC scheme, the packet error probability decreases by reducing the occurrence of retransmissions and hence packet delays. The total expected packet delay for cooperative MIMO MAC can be evaluated similar to the equations (4.14), (4.15) and (4.16) described in section 4.4.3. For the dynamically selected group size with threshold scheme, the delays of uncoded and STC schemes are evaluated.

5.5 RESULTS AND DISCUSSION

The analysis of the cooperative MIMO MAC protocol is carried out using MATLAB 7. The performance of proposed threshold based cooperative MIMO MAC protocol with STC and uncoded schemes are evaluated in terms of energy consumption and packet delay with and without neighbouring network traffic. The parameters considered for simulation are as described in Table 4.1.

When the nodes are busy with data transmissions of other source nodes the cooperative nodes do not always respond immediately to the recruiting message sent by the source node. Under this condition the source node may wait to recruit the busy node or proceed with the available nodes for data transmission.

5.5.1 Performance Analysis of Uncoded MIMO Scheme

The energy consumption of uncoded system for the proposed threshold based MAC protocol is shown in Fig.5.2. The energy consumption is less when 4×4 cooperative nodes are used at transmit and receive cluster. This reduction in energy consumption is due to diversity gain of cooperative MIMO systems. It is also observed from this figure that the proposed scheme outperforms fixed group size (2×2, 3×3 and 4×4) MIMO scheme by changing the cooperative threshold according to the queue length at the sender. The dynamic group size selected using cooperative threshold scheme is 4×4 MIMO configuration as it minimises the energy expended on recruiting and time spent on waiting for packet retransmission.

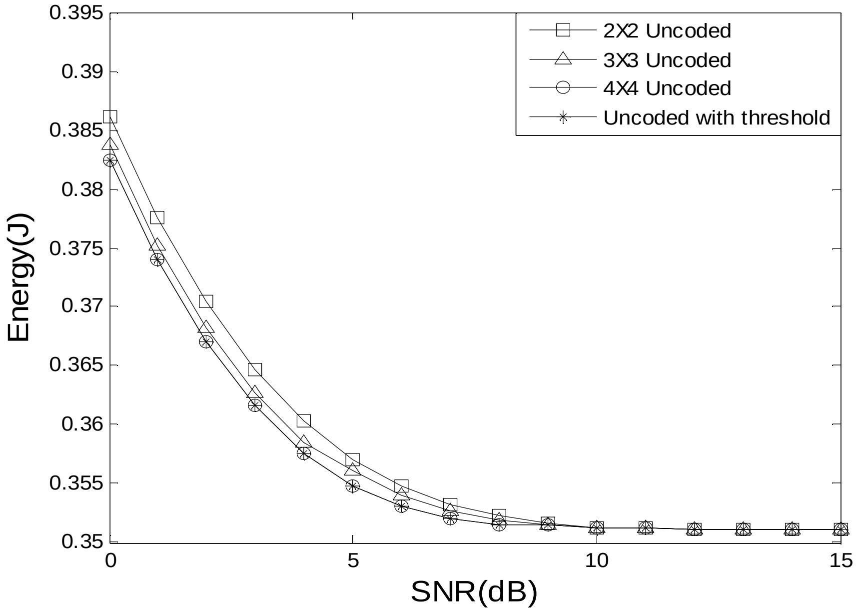

Fig.5.2. Energy consumption of uncoded scheme for fixed size MIMO configurations and cooperative threshold

The delay incurred with the proposed threshold based cooperative MIMO MAC protocol is plotted in Fig.5.3.

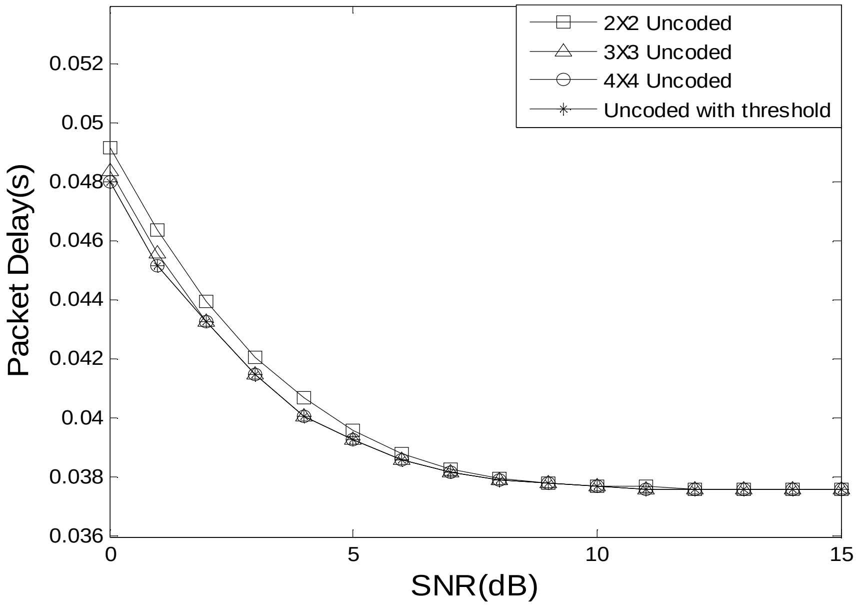

Fig.5.3. **Packet delay of uncoded scheme for fixed size MIMO configurations and cooperative threshold**

The delay keeps reducing with the increase in diversity order due to increase in the number of receiving cooperative nodes. The decrease in delay is due to less SER and fewer retransmissions in the system. It is clear that the proposed scheme chooses the dynamic group size 4×4 based on cooperative threshold as it has fewer data retransmissions and results in a smaller packet latency of 2% than 2×2 MIMO scheme.

5.5.2 Performance Analysis of STBC MIMO Scheme

Similar performances as that of uncoded scheme are obtained shown in Fig.5.4 and Fig.5.5 for energy consumption and delay with STBC coding technique with threshold scheme. It is observed that 4×4 is the dynamic group size selected with cooperative threshold as it incurs lesser energy and delay. This is due to the diversity gain exploited by the use of STBC coding. Comparing the performance of the system with the uncoded scheme shown in Fig.5.2 and Fig.5.3 significant reduction in energy and delay is observed owing to the less transmission errors.

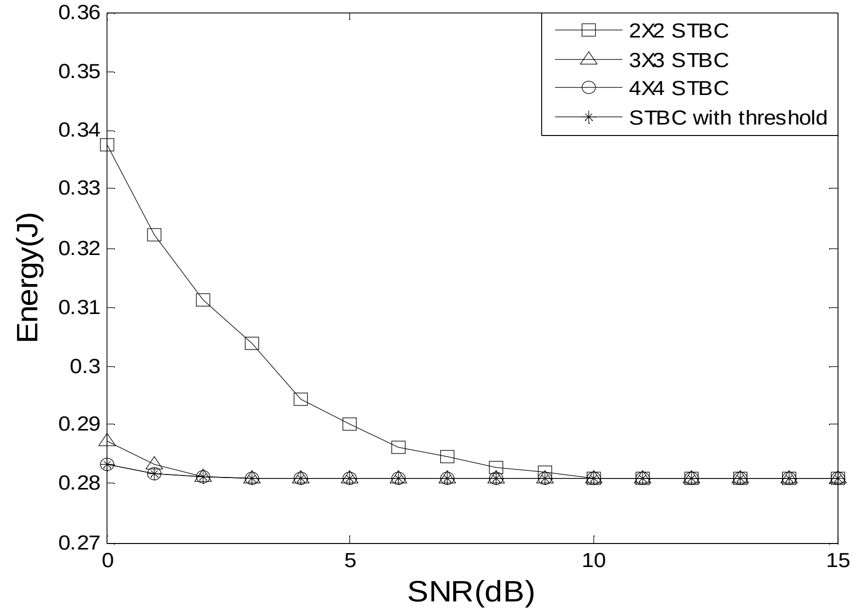

Fig.5.4. **Energy consumption using STBC scheme for various MIMO configurations and cooperative threshold**

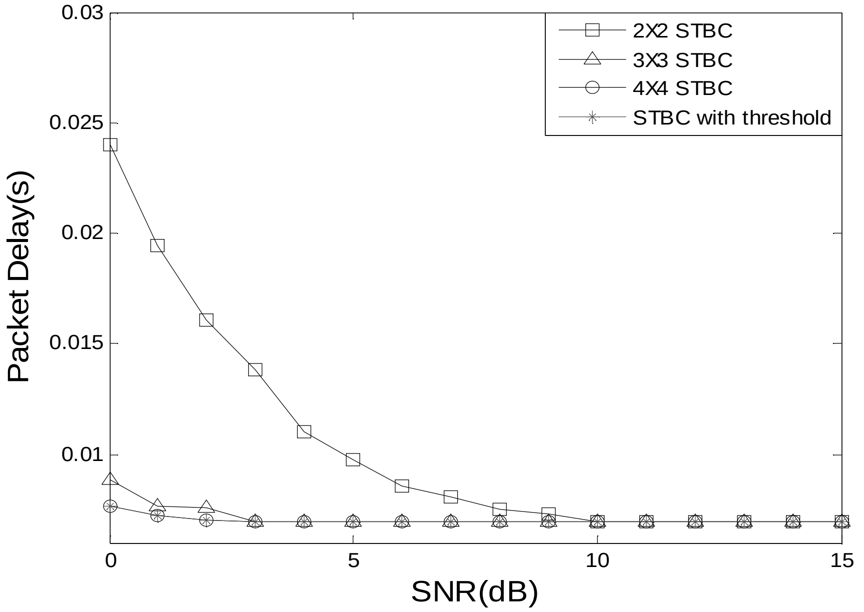

Fig.5.5. **Packet delay using STBC scheme for various MIMO configurations and cooperative threshold**

5.5.3 Performance Analysis of STTC MIMO Scheme

The energy and delay performance of STTC is shown in Fig.5.6 and Fig.5.7 for the threshold based MAC scheme.

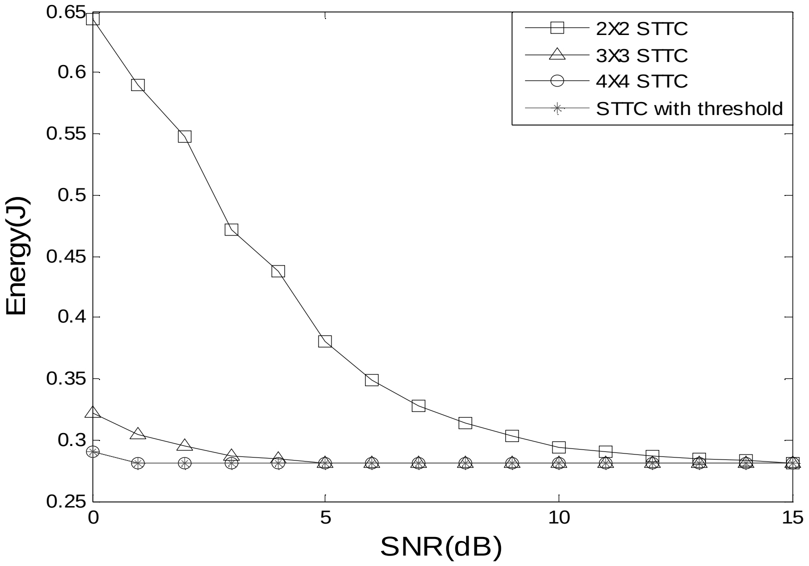

Fig.5.6. Energy consumption using STTC scheme for various MIMO configurations and cooperative threshold

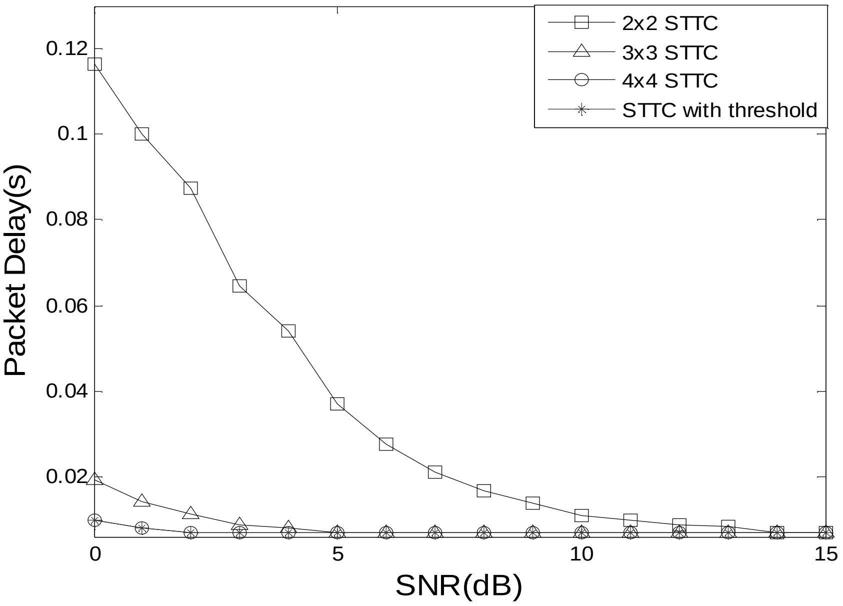

Fig.5.7. Packet delay using STTC scheme for various MIMO configurations and cooperative threshold

With STTC coding, 4×4 is the dynamic group size selected with cooperative threshold as it incurs less energy and delay. Comparing the performance of the system with the STBC scheme shown in Fig.5.4 and Fig.5.5 STTC degrades to smaller extent as it introduces additional hardware complexity in decoding.

5.5.4 Performance Analysis of Uncoded MIMO Scheme with Neighbouring Traffic

The energy consumption of uncoded system for the proposed MAC protocol with cooperative threshold in the presence of neighbouring network traffic is shown in Fig.5.8.

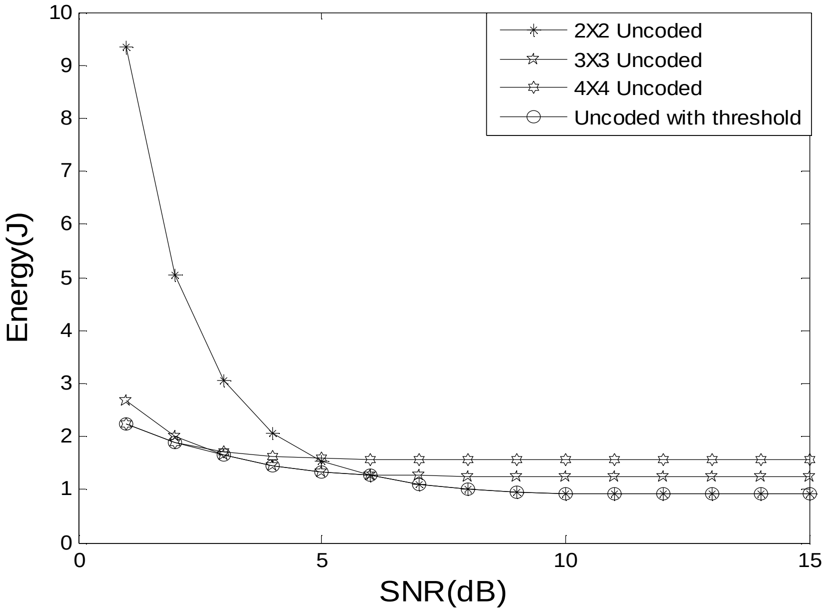

Fig.5.8. Energy consumption of uncoded scheme with neighbouring traffic

At lower SNRs, the MIMO configuration with diversity order 4×4 performs better and has reduction in energy consumption of about 78% when compared to 2×2 MIMO system. However as the SNR increases beyond 5 dB, the 2×2 cooperative sending and receiving group sizes consume lower energy of about 45% when compared with 4×4 taking into account the neighbouring traffic conditions of the network. This reduction in energy consumption with 2×2 configuration is due to fewer attempts required to recruit their neighbours for cooperative MIMO data transmission. It is also observed that the proposed scheme outperforms fixed group size MIMO scheme by changing the cooperative threshold according to the queue length at the sender. The dynamic group size selected using cooperative threshold scheme varies as it selects the group size that has minimum energy expended on recruiting and time spent on waiting for the required number of nodes in retransmission.

Using threshold policy the dynamic cooperative group size selected is 4×4 for SNR up to 3 dB, 3×3 up to SNR 6 dB and 2×2 above SNR 6 dB. This is because of lesser channel contention with lesser diversity orders. As the SNR increases, the energy consumption decreases and this is due to the lesser error rates achieved owing to the diversity gain of MIMO systems.

The delay incurred for the uncoded scheme with cooperative threshold is plotted in Fig.5.9. It is clear that the proposed scheme chooses the group size (4×4, 3×3 and 2×2) dynamically based on cooperative threshold as it utilises lesser recruiting time to recruit the neighbours for data transmission.

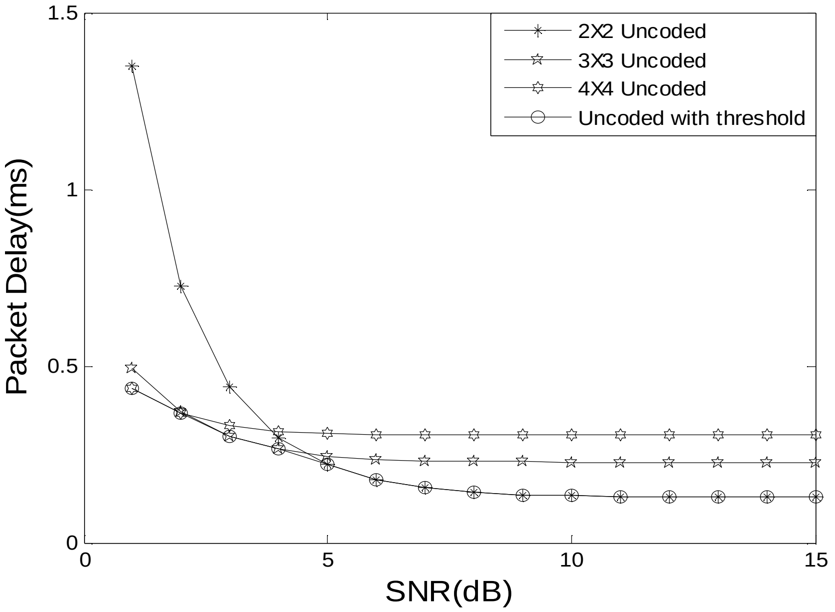

Fig.5.9. Packet delay of uncoded scheme with neighbouring traffic

5.5.5 Performance Analysis of STBC MIMO Scheme with Neighbouring Traffic

Similar graphs as that of uncoded schemes are obtained as shown in Fig.5.10 and Fig.5.11 for energy consumption and delay with STBC coding technique for various fixed sending and receiving group size (4×4, 3×3 and 2×2) with and without threshold scheme.

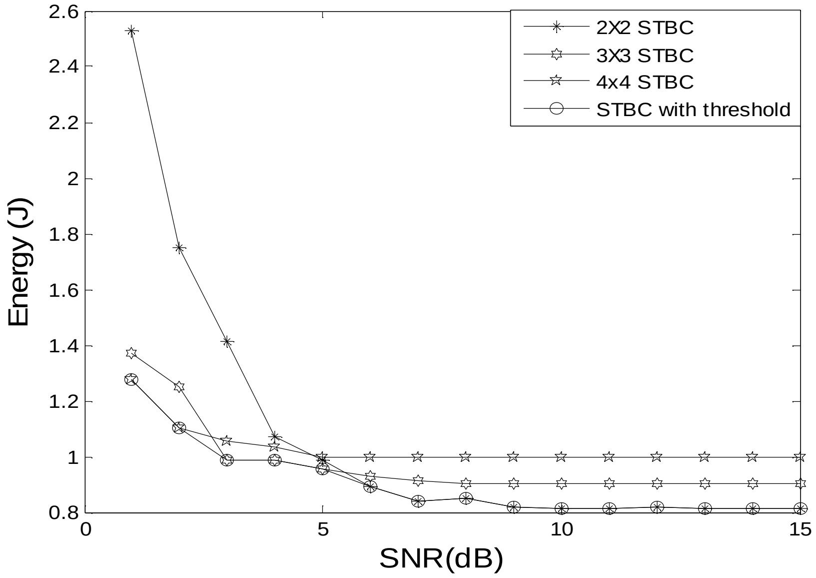

Fig.5.10. Energy consumption of STBC scheme with neighbouring traffic

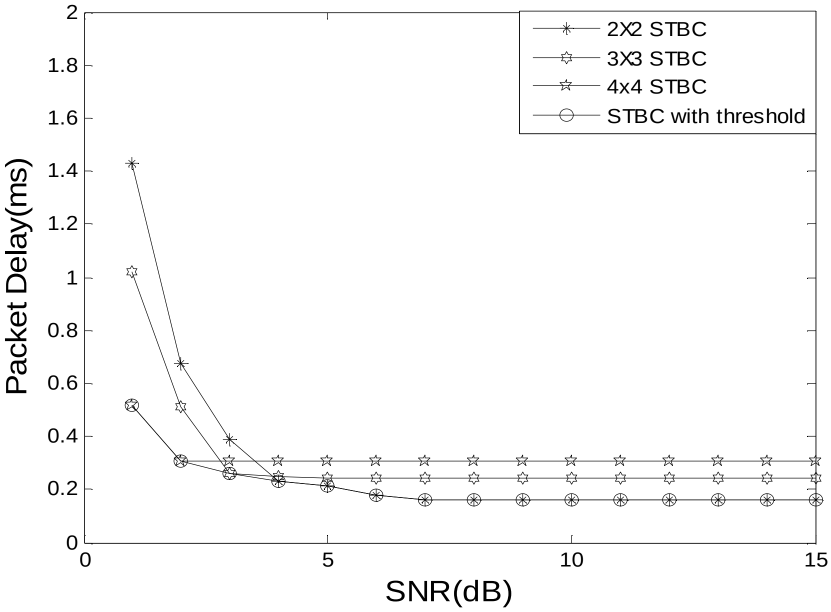

Fig.5.11. Packet delay of STBC scheme with neighbouring traffic

Taking into account the neighbouring traffic of the system it is vivid from the results (Fig.5.10 and Fig.5.11) that using threshold policy the dynamic cooperative group size selected is 4×4 for SNR up to 2 dB, 3×3 up to SNR 4 dB and 2×2 above SNR 5 dB. This dynamic group size chosen varies with SNR and is based on lesser energy and time spent on nodes for packet transmission using threshold policy.

5.5.6 Performance Analysis of STTC MIMO Scheme with Neighbouring Traffic

Similar performances have been observed for STTC scheme in terms of energy and delay taking into account the neighbouring network traffic and are shown in Fig.5.12 and Fig.5.13. It is clear from the results that the threshold scheme dynamically selects the cooperative group size 4×4, 3×3 and 2×2 based on lesser energy consumption and delay involved in packet transmission.

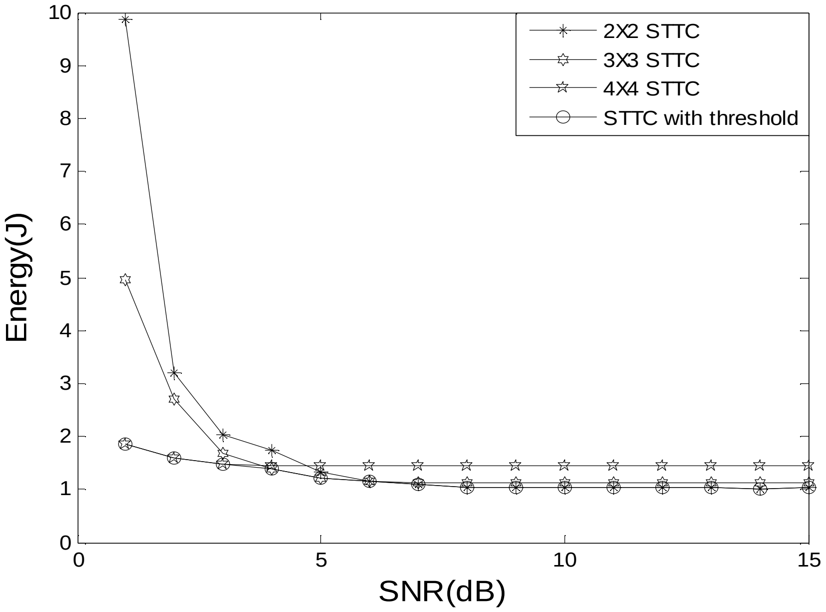

Fig.5.12. Energy consumption of STTC scheme with neighbouring traffic

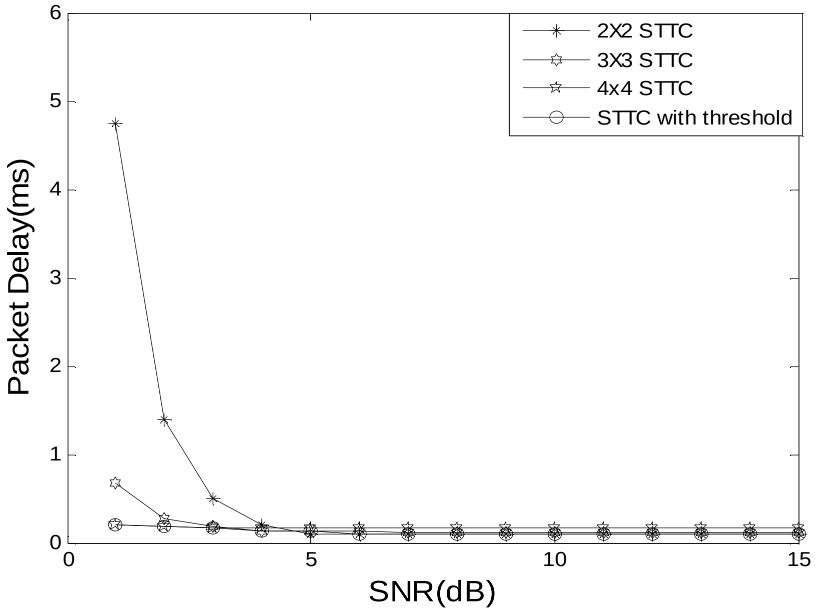

Fig.5.13. Packet delay of STTC scheme with neighbouring traffic

5.6 SUMMARY

Thus cooperative MIMO transmission scheme along with the threshold based MAC protocol is proposed to dynamically select the cooperative group size between the source and destination. The proposed MAC protocol enables transmission of data packets with shorter delay and lesser energy consumption even under extreme fading conditions prevailing in the wireless channel. The performance of the cooperative MIMO MAC system is evaluated for uncoded scheme, STBC and STTC system in terms of energy and delay with and without neighbouring traffic.

The dynamically chosen cooperative group size with threshold based MAC scheme is 4×4 without considering neighbouring traffic. Taking into account the neighbouring traffic in the system and using threshold policy the cooperative group size dynamically varies with SNR. When SNR reaches 5 dB, the total energy consumed and delay decreases as the order of diversity increases (4×4). As SNR increases, the lowest diversity order (2×2) has the minimum energy and delay because lesser number of nodes are recruited and used for data transmission as well as reception. STBC scheme provides better performance in terms of energy and delay. This is due to the fact that STBC has lesser decoding complexity and provides better diversity gain compared with STTC scheme.

CHAPTER 6

MIMO ROUTING SCHEME

6.1 INTRODUCTION

Wireless sensor network requires robust and energy efficient routing protocols to minimise the energy consumption as much as possible [108-111]. However, the lifetime of sensor network reduces due to the adverse impacts caused by channel fading and interference. To maximise the network lifetime, cluster based cooperative MIMO routing schemes are suggested for sensor networks.

Two MIMO routing schemes are proposed in this chapter extending LEACH protocol using STBC [49] to achieve higher energy savings and diversity gain. The first scheme termed as C-LEACH protocol enables cooperative MIMO communication through the selection of cooperative sending and receiving nodes in each cluster. The second scheme incorporates cooperative MIMO communication by letting cluster heads to transmit data to sink cooperatively called CH-C-LEACH protocol. The performance of the proposed cooperative MIMO schemes such as C-LEACH and CH-C-LEACH are evaluated in terms of energy efficiency to improve the lifetime of sensor network.

6.2 HOMOGENEOUS SENSOR NETWORK

In homogeneous sensor network, all the nodes are identical in terms of energy resources. In this network, the nodes are grouped into clusters with each cluster having a cluster head node to transmit the sensed data to sink. The cluster heads chosen apriori are fixed and serve for the entire lifetime. The disadvantage of this approach is that the fixed cluster head node drains its energy resource and does not guarantee the network lifetime [14]. To ensure the lifetime of the homogeneous network, LEACH protocol for sensor network has been devised [31].

6.2.1 LEACH Protocol

In LEACH protocol, the role of cluster heads are rotated among the sensors, thereby evenly distributing the energy load of being a cluster head [15,16]. The operation of LEACH protocol is divided into rounds as shown in Fig.6.1. Each round begins with a set-up process where the clusters are organised and is followed by a steady-state process where the sensed data is transferred to the cluster head and inturn to the sink [31,76].

i) *Set-Up Process*

Each sensor i elects itself to be a cluster head at the beginning of round r+1 with probability $P_i(t)$. $P_i(t)$ is chosen such that the expected number of cluster head nodes for this round is m. This choice of probability for becoming a cluster head is based on the assumption that all nodes start with an equal amount of energy, and that all nodes have data to send during each frame. If nodes have different amounts of energy, the node which have more energy available than other nodes and have not been cluster head previously becomes a cluster head. Once the nodes have elected themselves to be cluster heads, they inform the other nodes in the network that they have chosen this role for the current round.

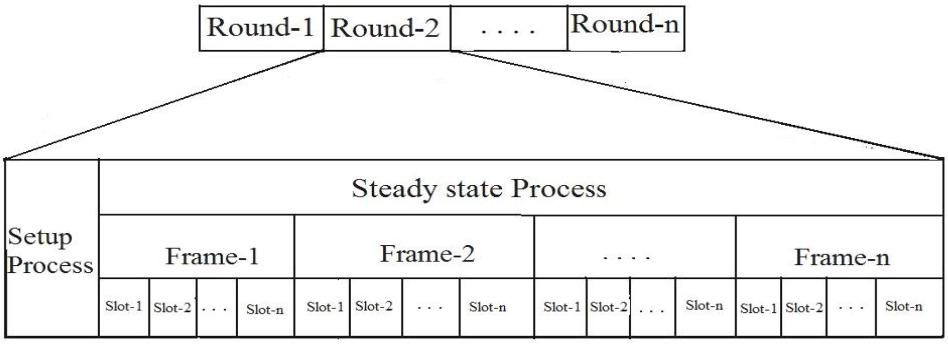

Fig.6.1. LEACH protocol operation

Each non-cluster head node determines its cluster by choosing the cluster head that requires the minimum communication energy, based on the received signal strength of advertisement from each cluster head. After each node has decided to which cluster it belongs, it informs the cluster head node that it will be the member of the cluster by transmitting a join- request message. A flow chart for the distributed cluster formation is shown in Fig.6.2. The cluster head node sets up a TDMA schedule and transmits this schedule to the nodes in the cluster. After the time division schedule is known by all nodes in the cluster, the set-up phase is complete and the steady-state process (data transmission) begins.

ii) Steady-State Process

The steady-state operation is broken down into frames, where nodes send their data to the cluster head atmost once per frame during their allocated transmission slot. The duration of each slot in which a node transmits data is constant, so the time to send a frame of data depends on the number of nodes in a cluster. Once the cluster head receives the data packet, it performs data aggregation and is transmitted to sink.

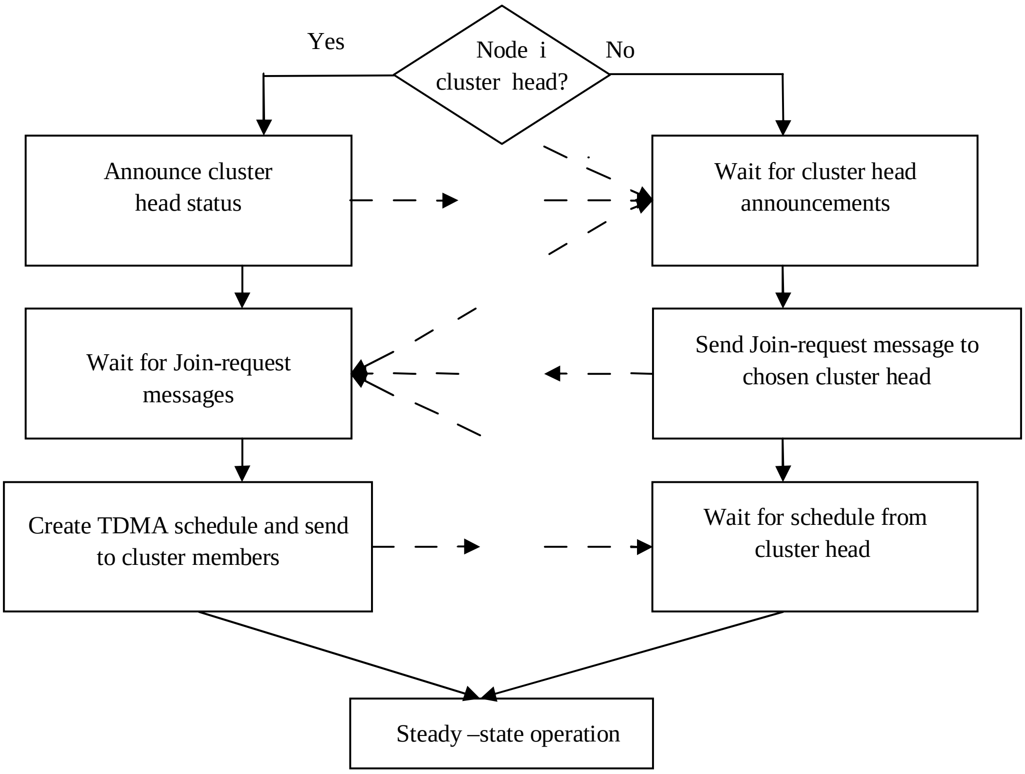

Fig.6.2. Flow chart of the cluster formation algorithm for LEACH protocol

The advantage of the LEACH approach is that the distributed cluster formation can be exploited without knowing the exact location of any of the nodes in the network. In addition no global communication is needed to set up the clusters. However, the original version of LEACH does not take into account the heterogeneity of nodes in terms of their initial energy, and as a result the energy consumption is not optimised.

6.3 HETEROGENEOUS SENSOR NETWORK

In the HSN model, H-sensors and L-sensors are randomly distributed in the field and clusters are formed as in Fig.6.3. The H-sensors and L-sensors serve as cluster head and non-cluster head nodes respectively. The basic idea of routing in HSN is described below. It consists of two parts: routing within a cluster and routing across clusters [83-85].

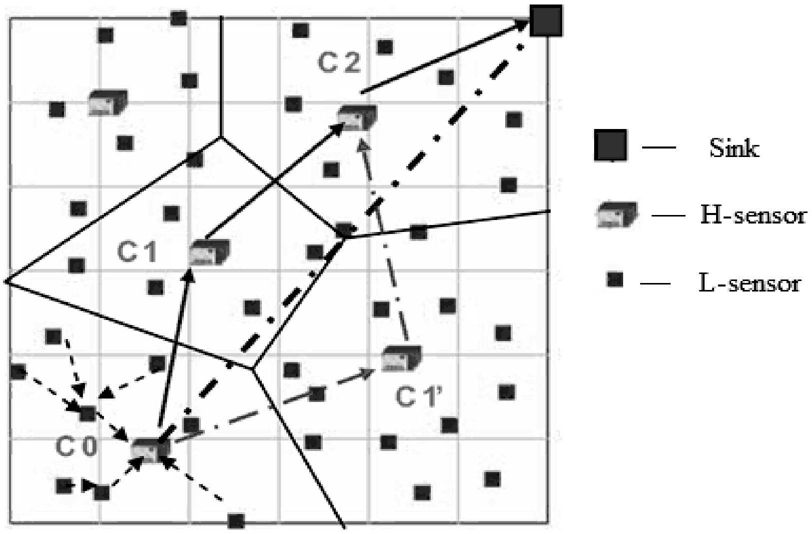

Fig.6.3. Heterogeneous sensor network model

i) *Intra-cluster routing*

Routing within a cluster (from an L-sensor to its cluster head) is referred to as intra-cluster routing. The L-sensor sends its location information to the cluster head during the cluster formation. The location of H is broadcasted to all L-sensors in the cluster. The L-sensors in a cluster form a tree, rooted at the cluster head so that each L-sensor sends packets to its H-sensor. If data from nearby L-sensor nodes are highly correlated, then a minimum spanning tree is adopted to achieve lesser energy consumption.

ii) *Inter-cluster routing*

Routing across clusters (from an H-sensor to the sink) is referred to as inter-cluster routing and is shown in Fig.6.3. After receiving data from L-sensors, cluster heads perform data aggregation via the H-sensor backbone. Each cluster head exchanges location information with the neighbouring cluster heads. When a cluster head wants to send a data packet to sink it draws a straight line between itself and the sink. The straight line intersects with several clusters, and these clusters are denoted as $C_0,C_1,\ldots,C_k$, which are referred to as relay cells.

If any cluster head in the relay cells is unavailable, then a backup path is used. A backup path is set up as follows: The current cluster head (say R1) draws a straight line between itself and the sink, and the line intersects with several cells $C'_1,...,C'_{k-1},C'_k$. If the next cell is the cell having the failed cluster head, R1 will use a detoured path to avoid the cell. The sequence of cells $C'_1,\ldots,C'_{k-1},C'_k$ will be the new relay cells and are used to forward the packet to the sink.

6.4 CLUSTER BASED COOPERATIVE MIMO ROUTING SCHEME

A heterogeneous cluster based sensor network model is considered as discussed in section 6.3 for cooperative MIMO routing. The sink node for the network model is assumed to have no energy constraints and is equipped with one or more receiving antennas. The sensor nodes are geographically grouped into clusters consisting of H-sensors, L-sensors, cooperative sending and receiving nodes. In the proposed scheme, the cluster heads and the cooperative nodes are reelected after each round of data transmission.

6.4.1 Cooperative Heterogeneous MIMO LEACH Scheme

The proposed cooperative MIMO LEACH (C-LEACH) transmission model is illustrated in Fig.6.4. The transmission procedure of the proposed scheme is divided into rounds. Each round has three phases:

i) *Cluster formation phase*

In this phase, clusters are organised and cooperative MIMO nodes are selected according to the steps described below:

a) *Cluster head advertisement*

Initially, when clusters are being created, each node decides whether or not to become a cluster head for each round as specified by the original LEACH protocol. Each self-selected cluster head, then broadcasts an advertisement message using CSMA MAC protocol.

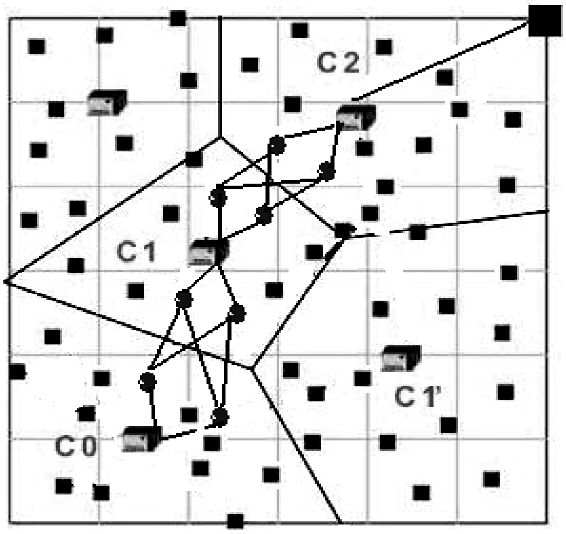

Fig.6.4. C-LEACH transmission model

b) *Cluster set-up*

Each non-cluster head node i.e., L-sensor node chooses one of the strongest Received Signal Strength (RSS) of the advertisement as its cluster head, and transmits a Join-Request (Join-REQ) message back to the chosen cluster head i.e., H-sensor. The information about the node’s capability of being a cooperative node, i.e., its current energy status is added into the message. If H-sensor receives advertisement message from another H-sensor y, and if the received RSS exceeds a threshold, it will mark H-sensor y as the neighbouring H-sensor and it records y’s Identifier (ID). If the sink receives the advertisement message, it will find the cluster head with the maximum RSS, and sends the sink position message to that cluster head marking it as the Target Cluster Head (TCH).

c) *Schedule creation*

After the H-sensors have received the join-REQ message, each cluster head creates a TDMA schedule and broadcasts the schedule to its cluster members as in original LEACH protocol. This prevents collision among data messages and allows the radio of each L-sensor node to be turned off until its allocated transmission time to save energy.

d) *Cooperative node selection*

After the cluster formation, each H-sensor will select J cooperative sending and receiving nodes for cooperative MIMO communication with each of its neighbouring cluster head [100,101]. Nodes with higher energy close to the H-sensor will be elected as sending and receiving cooperative nodes for the cluster.

In this phase, the cluster head will broadcast a Cooperative Request (COOPERATE-REQ) message, to each cooperative node which contains the ID of the cluster itself, the ID of the neighbouring H-sensor y, the ID of the transmitting and receiving cooperative nodes and the index of cooperative nodes in the cooperative node set for each cluster head to each cooperative node. Each cooperative node on receiving the COOPERATE-REQ message, stores the cluster head ID, the required transmitted power and sends back a cooperate-acknowledgement message to the H-sensor.

ii) *Routing table construction*

The H-sensor maintains a routing table which contains the destination cluster ID, next hop cluster ID and the IDs of cooperative sending and receiving nodes. Each cluster head will inform its neighbouring cluster heads of its routing table. After receiving route advertisements from neighbouring cluster heads, the cluster heads will update the routing table according to the route cost and advertise to its neighbouring cluster heads about the modified routes. Then the TCH will flood a target announcement message containing its ID to each H-sensor to enable the creation of transmission paths to the sink.

iii) *Data transmission phase*

In this phase, the L-sensors will transmit their data frames to the H-sensor as in LEACH protocol during their allocated time slot. Each cluster member will transmit its data as specified by TDMA schedule and will sleep in other slots to save energy. The duration and the number of frames are the same for all clusters.

After a cluster head receives data frames from its cluster members as shown in Fig.6.4, it performs data aggregation to remove redundant data and broadcasts the data to J cooperative MIMO sending nodes. When each cooperative sending node receives the data packet, they encode the data using STBC [49] and transmit the data cooperatively. The receiving cooperative nodes use channel state information to decode the space time coded data. The cooperative node relays the decoded data to the neighbouring cluster head node and forwards the data packet to the TCH by multihop routing**.**

6.4.2 Cluster Head Cooperative Heterogeneous MIMO LEACH Scheme

To further prolong the network lifetime, a CH-C-LEACH scheme is proposed and is illustrated in Fig.6.5. In this scheme the cluster head nodes cooperate and pair among themselves to transmit data cooperatively rather than selecting the cooperative sending and receiving groups in each cluster as specified in section 6.4.1. The transmission procedure of the proposed scheme is split into rounds and each round has four phases:

i) *Cluster formation phase*

During this phase, clusters are organised following the same procedure of C-LEACH scheme described in section 6.4.1.

ii) *Intra-cluster transmission and data aggregation*

In this phase, the L-sensor sends its packets to the H-sensor. The cluster head then performs data aggregation. At this point, each cluster head knows the volume of data it needs to transmit to the sink.

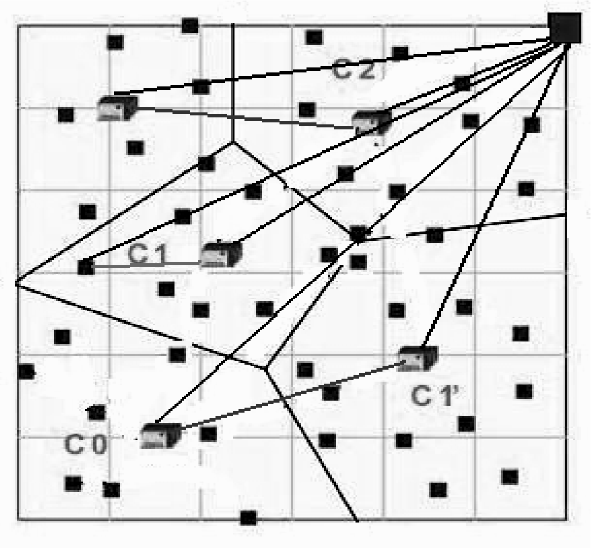

Fig.6.5. CH-C-LEACH transmission model

iii) *Data volume advertisement*

In this phase, the H-sensors inform each other about their data volume by broadcasting a short message that contains the node's ID and the volume of data it needs to transmit. All the messages are recorded by each H-sensor. Besides, according to the received signal strength of the advertisement, each cluster head estimates the distances to all other cluster heads and records the information.

iv) *Data exchange and cooperative transmission*

In this phase each H-sensor gets paired with other H-sensor and transmits data cooperatively. The flow chart of data transmission in CH-C-LEACH scheme is shown in Fig.6.6 and is described below:

a) *Sorting and division*

Based on the volume of data available at cluster head, each CH sorts the data and gets the reordered sequence for pairing to enable cooperative MIMO data transmission [103].

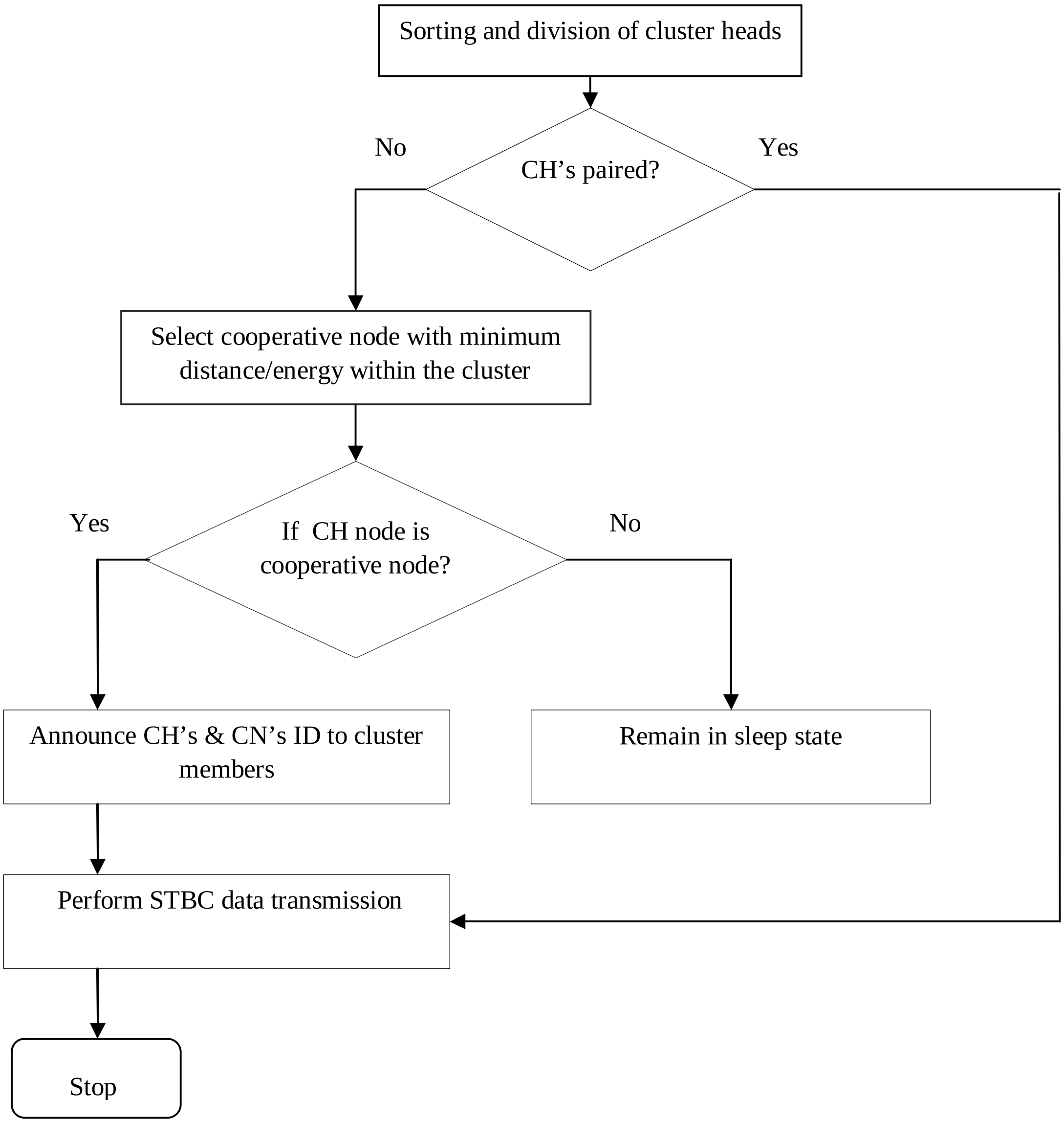

Fig.6.6. Flow chart of data transmission in CH-C-LEACH scheme

b) *Cooperative node selection and transmission*

If the number of H-sensors is odd, one of the H-sensor selects a cooperative node that has minimal distance and energy with the cluster head. This H-sensor informs the selected cooperative node by broadcasting a short message containing the cluster head's ID, the selected node's ID and an appropriate transmission time that the pair needs to transmit data to sink. Upon receiving the message, all nodes except this pair of nodes can turn off their radio components to save energy. The cluster heads wakes up at time T, and other non-cluster head nodes can remain in the sleep state till the next round. The H-sensor node sends its data to the selected cooperative node, and they encode the data using STBC [49] and transmit the encoded data to the sink cooperatively.

6.5 ENERGY CONSUMPTION MODEL OF THE PROPOSED SCHEME

The energy consumed during each round of data transmission using C-LEACH scheme results [50,100] from the following operations: L-sensor transmitting their data to the H-sensor, routing table constructed by the H-sensor, cluster head transmitting the aggregated data to the cooperative nodes, cooperative node transmitting the data to the receiving cooperative nodes and to the receiving H-sensor.

The energy consumed in CH-C-LEACH results from the cluster members transmitting their data to the H-sensor, cluster head transmitting the aggregated data to the cooperative cluster head and H-sensor nodes cooperate to transmit the data to the sink.

i) *Energy consumption of cluster member*

The energy consumed by the source nodes i.e., L-sensor to transmit one bit data to the cluster head node for C-LEACH and CH-C-LEACH scheme is given by

$$E_{bs}(k_c) = -\frac{1}{\pi k_c}(1+\alpha)N_f \sigma^2 \ln(p_e)G_1 M^2 M_l + \frac{P_{ct}+P_{cr}}{B} \quad (6.1)$$

where k_c is the number of clusters

α is the efficiency of radio frequency (RF) power amplifier

N_f is the receiver noise figure

$\sigma^2=N_0/2$ is the power spectral density of AWGN channel

p_e is the bit error probability

G_1 is the gain factor

M is the network diameter

M_l is the link margin

P_{ct} is the circuit power consumption of the transmitter

P_{cr} is the circuit power consumption of the receiver

B is the bandwidth

The total number of bits transmitted by L-sensor to the cluster head in each round is given by

$$S_1(k_c) = \left[\frac{N}{k_c}\right] F_n ps \quad (6.2)$$

where N is the number of sensor nodes

F_n is the number of frames in each round

p is the probability that the node has data to transmit

s is the packet size

The energy consumed by a cluster member to transmit data to the cluster head is given by

$$E_s(k_c) = k_c S_1(k_c) E_{bs}(k_c) \quad (6.3)$$

ii) *Energy consumption of cluster heads*

To construct the routing table, the energy consumed by the H-sensor node for C-LEACH scheme is given by

$$E_r(k_c) = k_c R_{ts} R_{bt} \left((1+\alpha) M_l N_f \frac{N_0 (4\pi)^2 (2M)^n}{p_e G_t G_r \lambda^2 \left(\pi k_c\right)^{k_c/2}} + \frac{P_{ct} + 4P_{cr}}{B} \right) \tag{6.4}$$

where R_{ts} is the routing table size

R_{bt} is the number of times for exchanging and updating routing table for each round

n is the path loss factor

G_t is the gain of transmitting antenna

G_r is the gain of receiving antenna

λ is the wavelength of transmission

The energy per bit consumed by the cluster head node to transmit the aggregated data to n_T cooperative nodes for C-LEACH and CH-C-LEACH scheme is given by

$$E_{bc0}(k_c, n_T) = -\frac{1}{\pi k_c}(1+\alpha) N_f \sigma^2 \ln(p_e) G_1 M^2 M_l + \frac{P_{ct} + n_T P_{cr}}{B} \tag{6.5}$$

The amount of data after aggregation for each round by H-sensor node is given by

$$S_2(k_c) = \frac{S_1(k_c)}{[(N/k_c)p\,agg - agg + 1]} \tag{6.6}$$

where agg is the aggregation factor

The energy consumed by cluster head node to transmit the aggregated data to n_T cooperative nodes is given by

$$E_{c0}(k_c, n_T) = k_c S_2(k_c) E_{bc0}(k_c, n_T) \tag{6.7}$$

iii) *Energy consumption of cooperative nodes*

The transmitter cooperative nodes of the cluster will encode the information using STBC and transmit to the receiving cooperative nodes. Consider the block size of the STBC code with F symbols and in each block pn_T training symbols are included and are transmitted in T_s symbol duration. The actual amount of data required to transmit the $S_2(k_c)$ bits is given by

$$S_e(k_c, n_T) = FS_2(k_c) / R(F - pn_T) \tag{6.8}$$

where R is the transmission rate

The energy consumed by n_T cooperative sending nodes to transmit MIMO data to the n_R cooperative receiving nodes for C-LEACH scheme is given by

$$E_{cs}(k_c, n_T) = S_e(k_c, n_T)\left((1+\alpha)M_l N_f \frac{n_T N_0 (4\pi)^2 (2M)^n}{p_e^{1/n_T} G_t G_r \lambda^2 (\pi k_c)^{n/2}} + \frac{n_T P_{ct} + n_R P_{cr}}{B}\right) \tag{6.9}$$

Similarly, the energy consumed by n_R receiving cooperative nodes or cluster head cooperative nodes to transmit data to the neighbouring cluster head/sink respectively for C-LEACH and CH-C-LEACH scheme is given by

$$E_{cr}(k_c, n_R) = S_e(k_c, n_T)\left((1+\alpha)M_l N_f \frac{n_R N_0 (4\pi)^2 (2M)^n}{p_e^{1/n_R} G_t G_r \lambda^2 (\pi k_c)^{n/2}} + \frac{n_R P_{ct} + P_{cr}}{B}\right) \tag{6.10}$$

iv) *Overall energy consumption for a round*

The energy consumption for each round of cooperative multihop MIMO data transmission for C-LEACH scheme can be obtained from Equations (6.3), (6.4), (6.7), (6.9) and (6.10) and is given by

$$E(k_c, n_T) = E_s(k_c) + E_r(k_c) + n_k E_{c0}(k_c, n_T) + n_k E_{cs}(k_c, n_T) + n_k E_{cr}(k_c, n_R) \tag{6.11}$$

where n_k is the average number of hops

The energy consumption for each round of data transmission for CH-C-LEACH scheme is given by

$$E(k_c, n_T) = E_S(k_c) + n_k E_{c0}(k_c, n_T) + n_k E_{cr}(k_c, n_R) \qquad (6.12)$$

6.6 RESULTS AND DISCUSSION

The analysis of the proposed cooperative heterogeneous MIMO routing schemes is evaluated in terms of energy consumption to maximise the lifetime of the sensor network using MATLAB 7. A sensing field with a population of N=100 nodes is considered for simulation with 80 L-sensors and 20 H-sensors randomly deployed over the region. The initial energy of L-sensor is set to 0.5 J and the energy of H-sensor is 2J. The communication parameters considered for the simulation [100,101] are summarised in Table 6.1.

Table 6.1 Simulation parameters for cooperative MIMO routing schemes

Parameter	Value
Efficiency of RF power amplifier	0.4706
Link margin	40 dB
Gain factor	30 dB
Power density of AWGN channel	-134 dBm/Hz
Receiver noise figure	10 dB
Carrier frequency	2.5 GHz
Bandwidth	20 KHz
Circuit power consumption of transmitter	98.2 mw
Circuit power consumption of receiver	112.6 mw
Antenna gain of transmitter and receiver	5 dB
Number of frames per round	2
Routing table size	100
Transmission rate	0.75
Packet size	2 kbits
Transmission probability of each node	0.8

The residual energy analysis of the proposed schemes C-LEACH, CH-C-LEACH and conventional LEACH scheme is portrayed in Fig.6.7. It is inferred from the figure that the proposed schemes consume lesser energy for data transmission than conventional LEACH scheme because of the diversity gain of the STBC system.

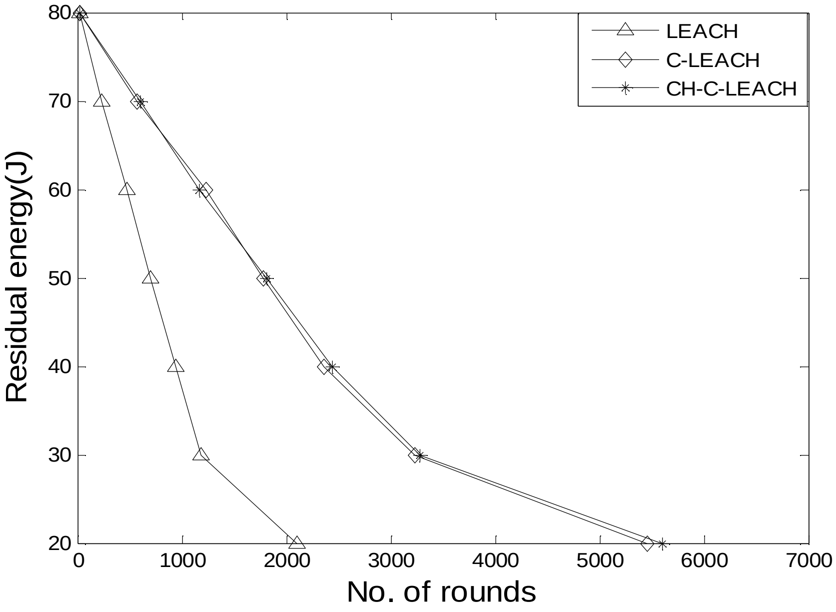

Fig.6.7. Energy analysis comparison of LEACH, C-LEACH and CH-C-LEACH scheme

The number of rounds of data transmission with 20% of remaining energy is 2000, 5500 and 5650 rounds for LEACH, C-LEACH and CH-C-LEACH schemes respectively. The LEACH scheme has a shorter lifespan when compared to proposed schemes due to channel fading and interference. The proposed CH-C-LEACH performs better than proposed C-LEACH by approximately 150 rounds. This is owing to the additional energy consumption of C-LEACH in choosing the cooperative sending and receiving nodes within a cluster during cluster set-up process.

The number of nodes alive for each round of data transmission is portrayed in Fig.6.8 for the proposed C-LEACH and CH-C-LEACH and conventional LEACH schemes. It is vivid from the figure that 60% of nodes in the

LEACH network die approximately in 1250 rounds whereas the proposed C-LEACH and CH-C-LEACH scheme prolongs lifetime by 3500 and 4000 rounds respectively. Conventional LEACH performs worser than proposed schemes due to larger energy consumption involved in the data transmission process.

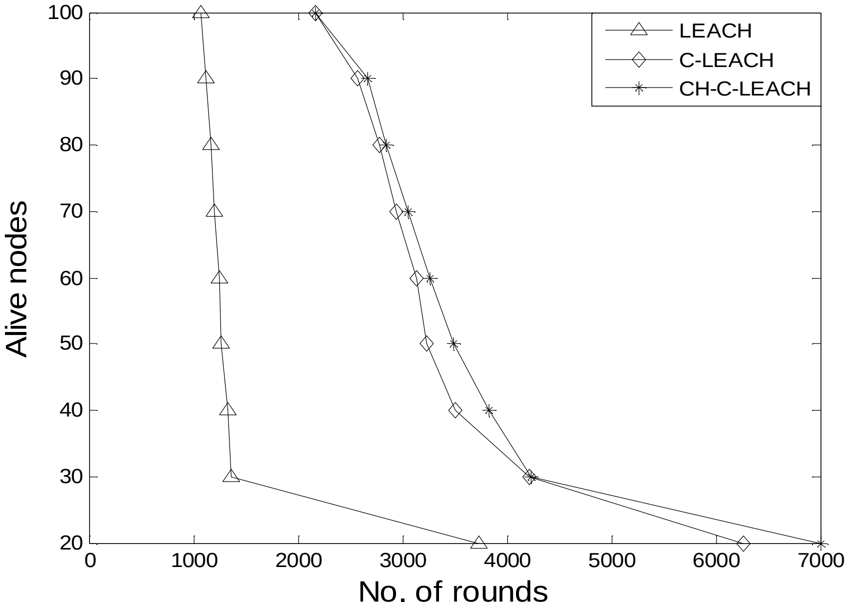

Fig.6.8. **Comparison of network lifetime of LEACH, C-LEACH and CH-C-LEACH scheme**

The number of rounds for every 10% of node death is observed for LEACH and the proposed schemes in Fig.6.9. It is evident that the lifetime of LEACH protocol is limited to 3750 rounds and the proposed scheme extends up to 6250 and 7000 rounds for C-LEACH and CH-C-LEACH respectively. The proposed schemes provide an extended lifetime of approximately twice the LEACH protocol. Also, the proposed CH-C-LEACH scheme performs better than the proposed C-LEACH scheme by extending the lifetime of approximately 750 rounds.

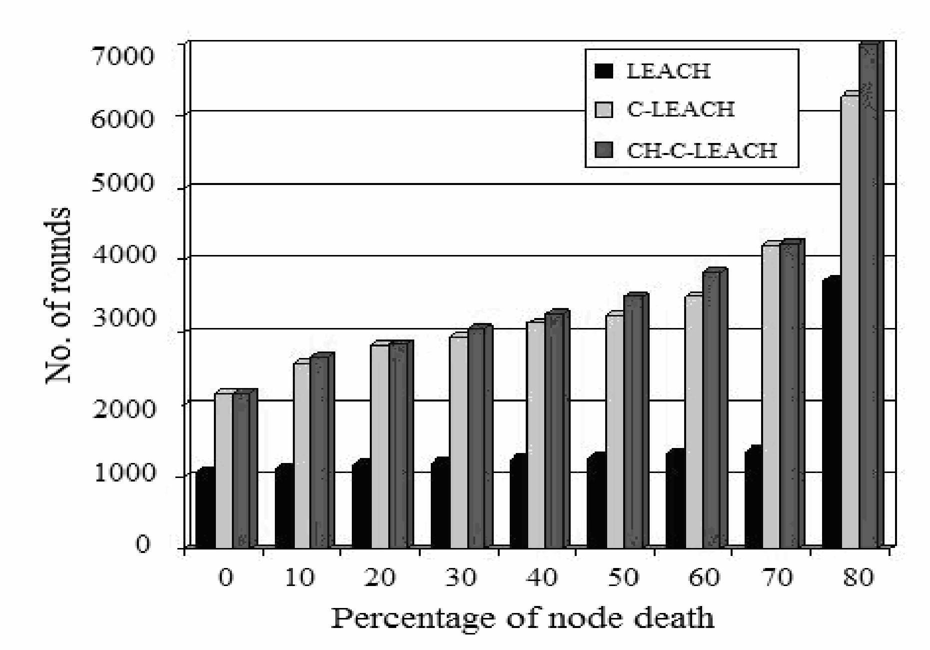

Fig.6.9. **Percentage of node death with LEACH, C-LEACH and CH-C-LEACH scheme**

6.7 SUMMARY

A cluster based cooperative MIMO scheme using STBC for WSN has been explored and the performance of the system is evaluated to minimise the energy consumption and increase the lifetime of sensor nodes. The simulation results reveal that the conventional LEACH protocol consumes more energy and has shorter lifetime of 3750 rounds due to the adverse channel fading effects. The proposed cooperative MIMO CH-C-LEACH performs better and extends 3250 rounds more than the LEACH scheme and 750 rounds more than the C-LEACH scheme for data transmission and saves up to 50% energy by the exploitation of the diversity gain of MIMO systems.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 GENERAL

An attempt has been made in the present work to enhance the lifetime of WSN through cluster based approach by using efficient routing, MAC and MIMO techniques. The summary, salient conclusions and scope for further research work are presented in this chapter.

7.2 SUMMARY

The advancements in wireless communication have necessitated the need of WSN with infrastructurefree support to intervene with hostile environment. The principal deliberation of WSN has been to save energy and to minimise the packet delay of the network. A cluster based network architecture has been developed to save energy significantly and support scalability of sensor nodes. The packet transmissions between the sensor nodes are handled by the MAC protocol for efficient channel utilisation. Reducing the channel collisions not only improves the throughput of the network, but also conserves the energy and minimises packet delay of the sensor network.

In the present work, an attempt has been made to develop a hybrid MAC protocol for cluster based sensor network for inter and intra-cluster communication to improve the sensor network lifetime. Moreover, channel fading and interference which increases the energy consumption of sensor nodes are mitigated by employing diversity techniques. Cooperative MIMO schemes that provide diversity gain are used to reduce the retransmission probability so as to improve energy savings. Diversity techniques involving space time codes such as space time block code and space time trellis code have been visualized in this work. In addition, a threshold based cooperative MAC protocol has been proposed to dynamically select the cooperative MIMO group size taking into account the neighbouring traffic in the network. Site diversity techniques are applied to provide the diversity gain. Further, to route the data from the sensing field in the presence of fading, a energy efficient MIMO routing schemes such as C-LEACH and CH-C-LEACH are propounded.

7.3 CONCLUSIONS

The performance of the proposed hybrid MAC system is examined through simulation analysis and compared with the conventional MAC schemes for clustering approach. It is evident from the results that BMA protocol exhibits 42% and 15% reduction in energy consumption than TDMA and E-TDMA scheme respectively in the intra-cluster communication. Moreover, dynamic scheduling scheme reduces packet transmission delay by 68%.

NanoMAC protocol provides significant performance improvement for inter-cluster communication. The energy expended for data transmission is almost 65% less than np-CSMA protocol. Also, the packet delay of nanoMAC protocol is reduced by 8% without any degradation in throughput. The reduction in energy consumption and delay of the proposed hybrid MAC protocol can significantly prolong the lifetime of the sensor network.

Further, cooperative MIMO scheme utilising STC is propounded to combat channel fading effects to ensure packet transmissions between sensor nodes. The performance of the cooperative MIMO MAC system is evaluated for various orders of diversity (2x2, 3x3 and 4x4) with space time coding techniques such as STTC and STBC. Simulation results disclose that 4x4 MIMO configuration with space time code, perform better than other diversity orders. It consumes 26% less energy for packet transmission than uncoded scheme. Also, the delay incurred in data transmission is reduced by around 89%.

A distributed threshold based MAC protocol for cooperative MIMO transmissions using space time codes for wireless sensor networks is proposed to ensure the stability of transmission queues at the nodes. The performance of the MAC scheme is evaluated by selecting the dynamic cooperative group size based on minimum energy and delay. The optimum group size obtained with the cooperative threshold without considering the network neighbouring traffic is 4x4. However, the dynamically chosen group size with cooperative threshold considering the neighbouring network traffic varies as 2x2, 3x3 and 4x4. Simulation results prove that STBC with cooperative threshold consumes less energy and delay for packet transmissions than uncoded scheme. The significant reduction in delay and energy results from the diversity gain accomplished with the coded MIMO systems.

Also, a cooperative MIMO routing scheme (C-LEACH and CH-C-LEACH) is proposed to maximise the network lifetime. The performance of the system is evaluated in terms of energy efficiency. Simulation results reveal that tremendous energy savings is achieved by adopting cooperative MIMO scheme among the clusters. The scheme saves 50% of energy by exploiting diversity gain and multihop communication among the cluster head nodes. Moreover, the proposed scheme prolongs the network lifetime with 50% of nodes remaining alive than LEACH protocol.

The outcome of the present work shows that the energy expended and transmission delay are reduced significantly with the help of MAC protocol, MIMO and cluster based routing approach among sensors. The proposed energy efficient techniques can increase the lifetime of network to a great extent to serve diverse applications.

7.4 SCOPE FOR FURTHER WORK

The following are some of the potential problems that might be interesting for researchers to pursue and explore in future.

i. The real time implementation of the system using hardware components with sensor nodes deployed in an environment can be worth exploring.
ii. Efforts can be made to provide an energy efficient solution by using error control code combining techniques in the cluster based cooperative wireless networks.
iii. The energy efficiency of MIMO MAC discussed in the present work has focused on QPSK modulation. It will be worthwhile to study the impact of the proposed protocol for the best modulation and transmission strategy.
iv. The effects of time synchronisation errors on the performance of cooperative MIMO systems can be explored to provide an energy efficient solution.
v. The energy efficiency techniques pertaining to the transport layer of sensor network to handle the communication between the sink and sensor node can be investigated.

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