STUDIES ON LIFETIME ENHANCEMENT TECHNIQUES FOR WIRELESS SENSOR NETWORK

THESIS

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CERTIFICATE

Certified that this thesis entitled **“STUDIES ON LIFETIME ENHANCEMENT TECHNIQUES FOR WIRELESS SENSOR NETWORK”** 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. R.VALLI** 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

Ad hoc networks have revolutionized wireless communications in the past few years, by complementing more traditional network paradigms such as, internet, cellular networks and satellite communications. By exploiting ad hoc wireless technology, various portable devices such as cellular phones, Personal Digital Assistants (PDAs), laptops, pagers etc., can be connected together with fixed equipment like base stations, wireless internet access points, etc., to form a sort of ‘global’, or ‘ubiquitous’, network. Although ad hoc 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 recent technological advances have enabled the development of low-cost, low power, and multifunctional sensor devices. These nodes are autonomous devices with integrated sensing, processing, and communication capabilities. Sensor 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.

Further, the distributed nature wireless communication networks give rise to many challenges related to their analysis, control, and management. The selfish nature of the nodes, development of decentralized control mechanisms, and fair allocation of system resources are the major issues in area of networks. Consequently, game theoretic methods are increasingly utilized to gain a deeper understanding of these complex problems and systems. Specifically, game theoretic models have been used in the context of internet pricing, flow and congestion control, routing, power control, and security.

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 and radio irregularity. To achieve high energy efficiency, Error Control Coding (ECC) has gained significant interest for large scale wireless sensor network. In this dissertation the applicability of game theory for power control problems with ECC in WSN has been investigated. In this approach, error detection and error correction ensure reliable delivery of data over these unreliable communication channels. Reducing the power consumed by the sensor nodes can be accomplished by selecting appropriate ECC.

Deployment of nodes in Wireless Sensor Network (WSN) is a challenging task due to its characteristics such as dynamically changing topology, lack of centralized authority and decentralized architecture. A proper node deployment scheme can lessen the complexity of problems like routing, data aggregation and communication in WSN. Moreover, it can extend the lifetime of WSNs by minimizing energy consumption. A sensor network can be deployed either with deterministic placement, where a particular quality of service can be guaranteed; or with random placement, where sensors are scattered possibly from an aircraft. Although the random node deployment is preferable in many applications, it is currently infeasible in most situations as the individual sensors are generally too expensive for this level of redundancy. Hence other deployment schemes are investigated. A game theoretic model with pricing for power control taking into account the residual energy of the nodes in a sensor network considering various deployment schemes have been propounded.

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 MIMO techniques to enhance the lifetime of WSNs by employing appropriate power control solution. The power control problem in virtual MIMO (VMIMO) WSN is modelled as a coalitional game to select the cooperative nodes for enabling packet transmission and obtain better utility by forming groups and controlling the power cooperatively rather than individually.

Another way to combat fading is the use of adaptive modulation which allows a wireless system to choose the highest order modulation depending on the channel conditions while ensuring that no harmful interference is caused to other nodes. Since the non-adaptive methods require a fixed margin to maintain acceptable performance when the channel quality is poor, adaptive approaches result in better efficiency by taking advantage of the favourable channel conditions. An energy efficient adaptive modulation and coding for power control and lifetime enhancement in WSN using game theoretic approach taking into account the residual energy of the nodes has been analysed. The game is designed such that, appropriate modulation and coding is selected based on the current channel condition. After the physical layer sets the optimal modulation level, it adjusts the transmission power to stabilize at the optimal transmission power by the feedback based power control scheme.

To summarise, an attempt has been made in the present work to enhance the network lifetime of WSN through game theoretic approach by employing efficient error control coding technique, deployment schemes, VMIMO and Adaptive Modulation and Coding (AMC). The related further study is to provide an energy efficient solution by using other power control techniques such as water filling algorithm in the game based approach.

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LIST OF ABBREVIATIONS

ACK	Acknowledgement
AMC	Adaptive Modulation and Coding
APC	Active power control
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BKY	Bleichenbacher, Kiayias, and Yung
bps	Bits per second
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CH	Cluster Head
CPU	Central Processing Unit
CS	Coppersmith and Sudan
CSI	Channel State Information
CTS	Clear to Send
dB	Decibels
DSP	Digital Signal Processing
ECC	Error Control Coding
FEC	Forward Error Correction
FSK	Frequency Shift Keying
HARQ	Hybrid ARQ
IEEE	Institution of Electrical and Electronics Engineers
LEACH	Low Energy Adaptive Clustering Hierarchy
MAC	Medium Access Control
MANET	Mobile Adhoc Network
MCS	Modulation and Coding Scheme
MIDRS	Multivariate Interpolate Decoding RS
MIMO	Multi Input Multi Output

MISO	Multi Input Single Output
M-QAM	M-ary Quadrature Amplitude Modulation
MMSE	Minimum Mean Square Estimator
NE	Nash Equilibrium
NFSK	Non-coherent Frequency Shift Keying
NRPG	Non-cooperative joint Rate and Power Control Game
NUM	Network Utility Maximisation
PAN	Personal Area Network
PDA	Personal Digital Assistant
PER	Packet Error Rate
PPC	Passive Power Control
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RS	Reed Solomon
RTS	Request to Send
SINR	Signal to Interference Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SPIN	Sensor Protocol for Information via Negotiation
STBC	Space Time Block Code
STC	Space Time Coding
STTC	Space Time Trellis Codes
TCM	Trellis Coded Modulation
TDMA	Time Division Multiple Access
THT	Tri-Hexagon Tiling
TPC	Transmission Power Control
TPCG	Transmit-Power Control Game
VMIMO	Virtual MIMO
WANET	Wireless Ad hoc Network
WSN	Wireless Sensor Network

LIST OF SYMBOLS

a	Constant
a_R	Area covered by the receiving range of a node
A	Network area
A_i	The set of actions available for a player ‘i’ to make a decision
$A(s_i)$	Pricing function
$A_R(s_i)$	Pricing function while considering residual energy
b	Number of bits per symbol
BER	Bit error rate
BER_{MIDRS}	MIDRS coded BER
BER_{RS}	RS coded BER
c	Pricing factor
d	Distance
$d_{minMIDRS}$	Minimum hamming distance of the MIDRS code
d_{minRS}	Minimum hamming distance of the RS code
E_i	Initial energy of the node
E_0	Residual energy of the node
E_{ir}	Residual energy of the i^{th} node
E_{kr}	Residual energy of the k^{th} node
E_m	Maximum energy of the node
E_t	Energy consumption of the node in the previous round
$f(\gamma)$	Efficiency function
F	Packet size
G	Game
G_T	Transmit symbol vector
H	MIMO channel matrix,
h_i	Path gain of node ‘i’
h_{ij}	Complex number corresponding to the channel gain between transmit antenna j and receive antenna i.
h_k	Path gain of node ‘k’
I_{M_t}	$(M_t \times M_t)$ identity matrix

j	Number of errors in a block of n_{RS} symbols
k_{MIDRS}	Number of information symbols in MIDRS code
k_{RS}	Number of information symbols in RS code
L	Number of information bits in a packet of size F bits
m_0	Modulation order
M_n	Number of encoders in MIDRS
M_r	Number of receive antennas
M_{sym}	Number of bits of each symbol that can be modulated by the type of MCS selected
M_t	Number of transmit antennas
n	Additive noise vector
n_{MIDRS}	Length of the code word in MIDRS code
n_{RS}	Length of the code word in RS code
N	Set of players
N_{hex}	Number of active nodes required for the hexagonal topology
N_{sqr}	Number of active nodes required for the square grid topology
N_{tri}	Number of active nodes required for the triangular topology
p_c	Coded symbol error probability
P_{MIDRS}	Probability of successful transmission of a packet for MIDRS code
PG	Processing gain
P_{RS}	Probability of successful transmission of a packet for RS code
r_I	Interference range
r_R	Receiving range of a node which is equal to the arm length of a regular polygon.
R	Data rate
R_{coding}	Coding efficiency
S	Strategy set
S'	Space of strategy profiles
s_i	Strategy profile of the i^{th} node
s_{-i}	Strategy profile of all the nodes but for the i^{th} node
s_k	Transmission power of k^{th} node
s_{max}	Maximum transmit power

$s_{i(MIMO)}$	Overall power consumption to transmit the data using cooperative communication
s_{min}	Minimum transmit power
t_{RS}	Error-correcting capability of the RS code
t_{MIDRS}	Error-correcting capability of the MID algorithm
T_{bc}	Number of time periods for transmission of one block of coded symbols
T_{co}	Lifetime of the sensor node which takes part in MIMO communication
T_{net}	Network lifetime
$T_{non\text{-}co}$	Lifetime of the sensor node which do not take part in MIMO communication
$T_i^{v_j}(s_i,s_{-i})$	Throughput of the node ‘i' with coalitional game
U_i	Payoff (utililty) function
$u_i(\text{pricing})$	Utility with pricing if a node is transmitting
$u_i^{v_j}$	Utility of the node within the coalition V_j
$u_i^{v_j}(\text{pricing})$	Utility function with pricing for power control game using VMIMO
$u_i(s_i,s_{-i})_{RS}$	Utility function of a node using RS code
$u_i(s_i,s_{-i})_{MIDRS}$	Utility function of a node using MIDRS code
$u_i^{v_j}(s_i,s_{-i})$	Utility of the i^{th} transmitting node using MIMO communication
$u_i^{v_j}(s_i,s_{-i})_{MIDRS}$	Utility function of the i^{th} transmitting node for hexagonal deployment using MIDRS codes in VMIMO WSN
$u_i(s_i,\gamma_i)$	Utility function for AMC
V	Partition of N, $V \subseteq N$.
$\lvert V_j \rvert$	Number of sensor nodes in V_j
W	Channel bandwidth
x_q	q modulated signals
$x_q\,*$	Conjugate of q modulated signals
x_i	Transmitted sequence from i^{th} cooperative node
x_j	Transmitted sequence from j^{th} cooperative node

x^i_t	Encoder output at time t for transmit cooperative node i
y	Received signal vector
Y	STBC transmission matrix
Y^*	Complex STBC transmission matrix
Y^H	Hermitian of Y
Y_t	Branch metric computed at receiver
z	Number of neighbours in the interference range
ρ	Node density
σ^2	Noise spectral density
υ	Characteristic function based on the network lifetime
$\eta_{eff,AMC}$	Ideal AMC
η_{RS}	Power efficiency using the RS code
η_{MIDRS}	Power efficiency using the MIDRS code
$\eta_{MIDRS\text{-}VMIMO}$	Power efficiency considering in hexagonally deployed VMIMO WSN using MIDRS codes
η_{VMIMO}	Power efficiency considering in VMIMO WSN

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Wireless communication has been experiencing its fastest growth period in history, due to enabling technologies which permit widespread deployment [1]. Wireless technology now reaches or is capable of reaching virtually every location on the face of the earth. Hundreds of millions of people exchange information every day using laptops, personal digital assistants (PDAs), pagers, cellular phones, and other wireless communication devices. Success of outdoor and indoor wireless communication networks has led to numerous applications in sectors ranging from industries and enterprises to homes and universities. No longer bound by the harnesses of wired networks, people are able to access and share information on a global scale nearly anywhere they venture.

There are two distinct approaches of enabling wireless communication. They are infrastructure or centralised topology and ad hoc or distributed topology. The first paradigm is to let the existing cellular network infrastructure carry data as well as voice [2]. The major intricacy is the difficulty in handoff smoothly from one base station to another base station without noticeable delay or packet loss. Another snag is that networks based on the cellular structure are limited to places having cellular network infrastructure. The second approach is to use Wireless Ad hoc Networks (WANET) which consist of mobile nodes communicating over a shared wireless channel [3, 4]. Contrary to cellular networks, where the nodes communicate with a set of carefully placed basestations, there are no basestations in wireless ad hoc networks. Any two nodes are allowed to communicate directly if they are within each other’s communication range, and also nodes use multihop routing to deliver their packets to distant destinations. These infrastructureless networks have many potential applications from Personal Area Network (PAN) to search and rescue operations.

Subsequently, the Mobile Ad hoc Networks (MANETs) have been developed to support scalability, mobility, adaptability and guarantee network performance [5]. It is an autonomous system in which mobile hosts connected by wireless links are free to move randomly and often close to humans. Such devices can communicate with another node that is immediately within their radio range (peer-to-peer communication) or one that is outside their radio range by using intermediate nodes to relay the packets from the source to the destination. Power consumption is not of prime importance in MANETs as its energy sources have high capacity and can be rejuvenated or replaced.

Technological progress enabled the spreading of embedded control in our daily life a step further. Eventually, a vision of “Ambient Intelligence” was realized, where many different devices gather and process information from many different sources to both control physical processes and to interact with human users. Therefore, a new class of network namely Wireless Sensor Network (WSN) has emerged in the last few years [6, 7]. This network consists of individual nodes that are able to interact with the environment by sensing or controlling physical parameters. The sensor nodes collaborate to fulfill their tasks by using wireless communication, as a single node is incapable of performing the task. WSNs are amenable to support a lot of different real-world applications such as environmental monitoring, surveillance, military, health and security [8-10].

1.1.1 Wireless Sensor Network Model

WSN is a particular type of ad hoc network, in which the nodes are ‘smart sensors’. These nodes are small devices equipped with advanced sensing functionalities, a small processor and a short-range wireless transceiver [11-14]. Sensor devices are deployed in strategic areas to gather data about the changes in their surroundings and report the changes to a data-sink. Also, they are expected to operate for several months to years. The data sink may be a fixed or mobile node capable of connecting the sensor network to wireless network infrastructure or to the internet where a user can access the reported data (Fig.1.1).

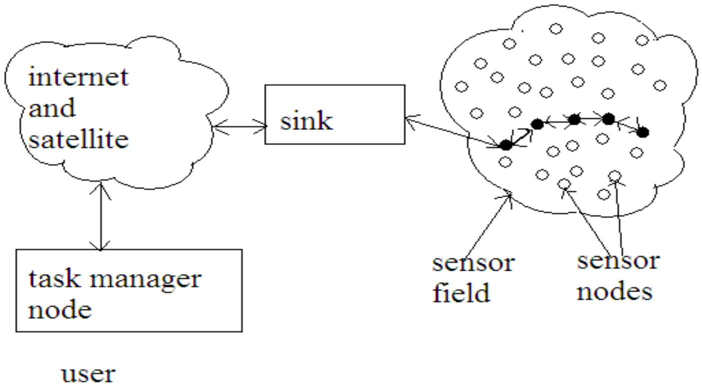


Fig.1.1. Basic sensor network model

1.2 GAME THEORY FOR WSN

As the demand for wireless services increases, efficient use of resources is significant. Though, reducing node energy consumption is important in ad hoc networks, it becomes very vital in WSN. In fact, the available energy is very limited in WSN due to low capacity battery. It is because of the reduced size of the sensor nodes. Despite this scarcity of energy, the network is expected to operate for a relatively longer time. As the replacing/refilling batteries are usually impossible, one of the primary design goals is to use this limited amount of energy as efficiently as possible.

Data transmission consumes the most energy among the various tasks of sensors such as sensing, computing and communication. Therefore, transmission at the optimal transmit power level is very crucial. It is due to the fact that a node will always try to transmit at high power levels just to make sure that the packets are delivered with a high success probability. Though, this increases the successful packet delivery, it proves to be counterproductive as energy is depleted faster. Also, transmitting at higher power levels increases the interference to other nodes, which in turn, will increase their power levels to combat the interference. This creates a cascade effect, where the nodes will continue to increase their power levels in response to the increased interference. Moreover, transmission at lower power levels will compromise the quality of communication. Hence, smart power control algorithms must be employed that find the optimal transmit power level for a node for a given set of local conditions. The problem of adjusting the transmission power of the nodes in a sensor network can be solved by using game theoretic framework.

Game theory [15-17] is the theory of decision making under conditions of uncertainty and interdependence which was basically used in economics and now has been predominantly used in wireless networks. The decision makers (players) in the game are the sensors and they have to cope with limited resources that impose a conflict of interests. In an attempt to resolve this conflict, sensors make certain moves such as transmitting now or later, adapting to transmission rate or changing their transmission power to maximize their payoffs (utility).

Each player in the game maximizes some function of utility in a distributed fashion. The game settles at Nash Equilibrium (NE) if one exists. A set of strategies (in this case transmit powers) is said to be at NE if no node can gain individually by unilaterally altering its own strategy. Since, the sensors act selfishly; this equilibrium point is not necessarily the best operating point from a social point of view. Hence pricing is introduced to improve efficiency of network. It appears to be a powerful tool for achieving a more socially desirable result.

Though there are several centralised game theoretic power control approaches for cellular networks [18], these centralised algorithms suffer from major drawbacks. Typically, centralization requires substantial communication overhead within a hierarchical architecture. Hence these centralized algorithms for power control cannot be applied for sensor networks. Recently, a number of decentralized schemes for efficient power management in sensor networks have been proposed [19]. These solutions have an ad hoc flavor as they are often inspired by heuristic arguments that typically work well for very specific scenarios but lack more general theoretical support for their performance. Another approach is to provide energy efficient power management by finding the optimal transmission power level with which a sensor node can transmit. The problem here arises due to the difficulty in characterizing the information that each sensor node has about the others. Hence, it is essential to arrive at the desired operating point in the incomplete-information scenario to enhance the lifespan of WSN.

1.3 SIGNIFICANCE OF POWER CONTROL

In a WSN, nodes share a single medium for communication. The performance of the sensor network depends on how efficiently and fairly the nodes in the network share this communication medium. A significant amount of node’s energy is spent on data transmission making communication the most energy-consuming event in WSN. One way to considerably reduce energy consumption is by applying transmission power control techniques to dynamically adjust the transmission power.

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 leaving a part of the network completely inactive 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 node activities that consume the highest amount of power.

Generally, all nodes in the WSN are assumed to use the same transmission power. Increasing the transmit power provides higher Signal to Interference Noise Ratio (SINR). This offers higher data rate and intuitively enhances the network throughput. However, high transmission power will also increase the interference to other nodes. Therefore, it is required to find an optimal transmit power that achieves maximum network throughput.

The design of efficient power control is constrained by a variety of factors, such as path loss, shadowing and fading which can severely degrade the Quality of Service (QoS). Further, when mobility is introduced, the problem becomes inevitably more difficult to solve. Existing power control mechanisms for WSNs may be classified into two main categories - Passive power control (PPC) and Active power control (APC) [20]. PPC seeks to save energy by switching the radio (transceiver) interface module off when not in use. APC adjusts the transmission power according to the network operating conditions by keeping the radio interface active.

Transmission Power Control (TPC) techniques improve the performance of the network in several aspects. First, power control techniques improve the reliability of a link. Upon detecting that link reliability is below a certain threshold, the MAC protocol increases the transmission power, improving the probability of successful data transmissions [21-23]. Second, only nodes which really must share the same space will contend to access the medium, decreasing the amount of collisions in the network. This enhances network utilization, lowers latency times and reduces the probability of hidden and exposed terminals [23]. Finally, by using a higher transmission power, the physical layer can use modulation and coding schemes with a higher bit/baud ratio [24, 25], increasing the bandwidth in the presence of heavy workloads, or decreasing it to maximize energy savings.

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 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 [26,27].

The transmission delay and energy are of prime importance in the process of evaluation of wireless communication systems. To ensure reliable communication over the radio channel, a system must overcome fading and interference and this can be achieved using MIMO technique. However, incorporating MIMO directly in WSNs is impractical as the node is usually limited in size. 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 of channel estimation at the receiver in WSN can be reduced from 64 to 8.

MIMO can be easily realised through Space Time Coding (STC) which transmits multiple copies of data stream across number of antennas [28]. 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.

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.

Since, the sensors are miniature battery powered devices, it is essential to conserve the battery resources to enhance the lifespan of WSN. This improvement in lifetime can be achieved through efficient power control techniques. Game theory is one of the promising technique to be applied for power control in WSN. The centralised power control algorithms for cellular network cannot be directly applied to WSN because of the communication overhead incurred. Hence, there arise a need for designing efficient decentralised game theoretic power control techniques for WSN to improve the lifetime of the network.

1.4 SCOPE OF THE WORK

Energy saving is the most important issue in research and development of WSN. Sensor networks have their limitations on energy due to interference, radio irregularity and fading. The search to accomplish this requirement is to consider power control mechanism with ECC, MIMO, appropriate node deployment schemes and AMC, which can reduce the power consumption of the nodes in the network.

Initially, iterative power control algorithms were proposed for cellular networks. These centralised algorithms investigate to find the power vector for all the nodes that minimizes the total power with good convergence. But, these centralised algorithms cannot be directly applied to sensor networks.

Subsequently, MIMO schemes have been used to coordinate the actions of distributed sensors to combat fading and radio channel interference of wireless medium. A drawback of MIMO techniques is that they require complex transceiver circuitry and large amount of signal processing power resulting in large power consumptions at the circuit level. This fact has so far precluded the application of MIMO techniques to wireless sensor networks consisting of battery-operated sensor nodes. In WSN, the MIMO is realised virtually with the cooperative sending and receiving groups. Diversity gain is achieved through space time code to reduce channel fading, interference to improve the performance of wireless communication systems.

Another approach to combat fading is to use adaptive modulation. It refers to the automatic modulation adjustment that a WSN can make to prevent weather-related fading from causing communication on the link to be disrupted. The radio system automatically changes modulation depending upon the prevailing channel condition. Since communication signals are modulated, varying the modulation also varies the amount of bits that are transferred per signal, thereby enabling higher throughputs and better spectral efficiencies. As a higher modulation technique is used, a better Signal-to-Noise Ratio (SNRs) is needed to overcome interference and maintain a tolerable Bit Error Rate (BER) level.

The game theory has been used to study various aspects of ad hoc and sensor networks. However, attention has not been focused on the power control problem in WSN using game theoretic approach. The use of Reed Solomon (RS) and Multivariate Interpolate Decoding RS (MIDRS) codes in the power control game has not yet been analysed. Also, a proper node deployment scheme that can extend the lifetime of WSNs by minimizing energy consumption has not been attempted. Furthermore, space time codes with game approach are yet to be explored for enhancing the performance of VMIMO based WSN. A power control game for AMC considering the energy of the nodes has not been fully analysed in WSN.

Hence, in the present work, an attempt is made to develop game theoretic framework that helps the nodes to decide on the optimal power levels for a specified objective given by the utility function. The power control in WSNs is done with efficient power control games using ECC, proper node deployment schemes, VMIMO schemes using cooperative Space Time Block Code (STBC) schemes and AMC.

1.5 OBJECTIVE OF THE WORK

An attempt is made in the present work to enhance the network lifetime of WSN through game theoretic approach by employing efficient ECC technique, deployment schemes, MIMO and AMC. The objectives set in the present work are as follows.

- To develop a game theoretic framework for power control using error control coding and evaluate the performance metrics such as utility, power efficiency and energy consumption of sensor network.
- To propound appropriate node deployment schemes and investigate the network performance using game approach considering residual energy check to achieve minimum energy consumption and enhanced network lifetime.
- To design a VMIMO scheme based on STBC using game theoretic approach to accomplish energy savings and to enhance the utility.
- To incorporate adaptive modulation and coding and analyse the system performance in terms of utility and energy consumption to prolong the network lifetime.

1.6 ORGANISATION OF THE THESIS

The Chapter 1 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 power control approaches for WSN system and game theory has been critically reviewed and is presented in Chapter 2. Summary of the review of literature is also furnished at the end of the chapter.

Chapter 3 narrates an energy efficient power control algorithm using ECC with game theoretic approach in WSN. The utility function devised mathematically for the proposed system is also presented. A detailed discussion on power control with the aid of simulation results for the system employing RS and MIDRS codes are incorporated in this chapter.

Chapter 4 deals with the analysis of various deployment schemes for WSN. A detailed discussion on the simulation results and the performance is succintly offered for the system. Utility and energy consumption employing game theoretic approach with and without energy check are also incorporated.

Cooperative MIMO system model using STBC with game approach is described in Chapter 5. The game theoretic approach for power control in VMIMO WSN using MIDRS code is also presented. The mathematical model to evaluate the performance of the system is cogently presented. Further, the simulation results in terms of utility, power efficiency, energy and lifetime analysis of both STBC and uncoded scheme for different diversity orders are also furnished.

Chapter 6 deals with the adaptive modulation and coding for energy efficient communication in WSN. The mathematical model representing the proposed system is devised and presented. Using this approach the energy efficiency to maximise the network lifetime is studied and quantified with results.

Chapter 7 concludes the thesis by emphasizing the major implications 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 extensive literature associated with the energy management in WSN was collected, critically reviewed and presented in this chapter. A comprehensive review of literature on evolution of game theory for WSN, MIMO and adaptive modulation 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 great zeal to minimize overall power consumption in order to maximise operational lifetime of sensor nodes. F. Akyildiz *et al.* [6] studied profoundly on WSNs to improve the lifetime and suggested the protocols and algorithms for sensor network applications. Sensor networks find many diverse applications ranging from low data rate event driven monitoring to high data rate real time industrial applications.

Gomez and Campbell analyzed the benefits of transmission power control in wireless multi-hop networks [21]. The outcome proved that per-link range adjustments outperform global range transmission adjustments by 50%. Thus, instead of globally defining a transmission range that keeps the network connected, wireless networks should adjust transmission ranges on each link. Also, it has been demonstrated that the average traffic capacity per node is constant on a TPC-aware network even if more nodes are added to a fixed-size area. However, this is not true in the case of fixed transmission range. For such networks, the traffic capacity decreases on adding more nodes due to increased interference.

Ammari and Das developed analytical models to evaluate how the transmission power affects latency and energy consumption in WSNs [29] and proved that increase in the distance traveled at each hop, decreases the end-to-end latency at the cost of a higher energy consumption. However, for a small distance per hop, energy consumption is less, but the latency increases as more hops must be traversed. Further, the creation of QoS classes was proposed with different latency and energy guarantees based on the transmission power employed on the communication. The analytical models, however, do not consider the effects of collisions on the communication.

Agarwal *et al.* proposed a distributed power control algorithm for MANETs [30]. Further, Jung and Vaidya proposed the adjustment of the transmission power for each frame in order to mitigate asymmetric links caused by transmission power variation [22]. Subsequently, Pires *et al.* extended this algorithm by adding a table in each node, which stores the transmission power used on previous transmissions [31]. Shan Lin *et al.* proposed a closed-loop TPC protocol for WSNs that approximates the ideal transmission power using linear equations [32]. Based on empirical data, it has been proved that link quality can be roughly approximated by the received signal strength using a linear relation.

Span [33] is a power saving technique for multi-hop ad hoc wireless networks, which reduces energy consumption without significantly diminishing the capacity or connectivity of the network. It is a distributed, randomized algorithm to turn off and on the battery in order to save power to the maximum. But, it uses fixed transmission power range and the algorithm is applicable for the low density wireless nodes such as IEEE 802.11 networks.

Burd *et al.*[34], Im, *et al.* [35., Sinha and Chandrakasan [36] and Pantazis *et al.* [20] proved that the application of PPC techniques can produce substantial energy savings by reducing the energy usage of the Central Processing Unit (CPU) in idle system states. Robin Kravets and Krishnam [37], Singh and Raghavendra [38], Srisathapornphat and Shen [39] and Ye *et al.* [40] proposed a number of heuristic algorithms for PPC to decide when to turn off the radio interface. However, since a large amount of power can be consumed in switching the transceiver back ON each time, this operation can sometimes prove inefficient. Therefore, operation in a power saving mode can only be energy efficient, if the time spent in the idle mode is greater than a certain predefined threshold [6].

Power-aware routing protocol is a typical APC technique that has received much attention of researchers. The reduction in transmission power levels can be achieved by managing data transmission paths [41, 42]. However, in order to obtain a satisfactory level of system performance in terms of power consumption, exact information in relation to the wireless channel gain is required [43]. Moreover, the use of intermediate hops to divide the distance between source and destination into shorter segments will not guarantee minimal transmission power [44]. An alternative APC technique which works based on the use of handshake signalling such as RTS/CTS (Request to Send/Clear to Send) frames have been proposed for optimizing power [45]. Since centralised information of the neighbour sensor nodes is a prerequisite here, the APC based on the use of handshake signalling is often complicated and time consuming.

In 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 such harsh environments. MIMO systems were proposed to use multiple transmitting and receiving antennas for signal transmission in physical layer. A. Paulraj *et al.* [46] demonstrated that multi input multi output systems support high data rates under the same transmit power and bit error rate performance requirements as that of single input single output system with minimum energy consumption.

MIMO techniques require complex transceiver 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 in a miniature sensor node may not be realistic. As a solution to the problem, cooperative MIMO has been explored by Shuguang

Cui *et al.* [47] to incorporate MIMO capability in a network of elements with 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 established that cooperative MIMO based sensor network provide better energy savings and end-to-end delay reduction than SISO scheme for transmission distance larger than a given threshold.

Subsequently, Sudharman K. Jayaweera [48, 49] 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 offers substantial energy savings in a wireless sensor network. However the system needs to be designed judiciously taking into account the transmission distance, transmission rate and time period.

Further, George N. Bravos *et al.* [50, 51] 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 between the transmitter and receiver 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 demonstrated 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 $d < 10$m and $n < 2.4$. Subsequently, a simple Cooperative Node (CN) selection algorithm has been proposed to achieve additional energy gains in the MIMO approach.

Yong Yuan *et al.* [52] examined a multihop virtual MIMO communication protocol using cross layer design to jointly improve the energy efficiency, reliability and end-to-end QoS provisioning in WSN. The protocol extends Low Energy Adaptive Clustering Hierarchy (LEACH) scheme suggested by Wendi R. Heinzelman *et al.* [53] 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 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. This approach is effective in minimising energy consumption and end-to-end delay.

Subsequently, Azzedine Boukerche and Xin Fei [54] presented a multihop virtual MIMO scheme [49, 50] 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 transmit diversity schemes for multiple antenna flat fading channel. V. Torakh *et al.* [55] 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 [56] 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 (STTC) 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.* [57] compared the performance of STBC and 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 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.* [58] investigated the effect of time synchronisation errors on the performance of the cooperative MISO systems. It was reported 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.* [59] 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. Zhang and Dai [60] described STBC and spatial multiplexing code on optimal transmission strategy. The scheme reduces the critical distance for virtual MIMO. The authors have also investigated the switching parameters of coding system for energy saving high rate data transmission in MIMO.

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. Su Yi *et al.* [61] 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. However, the link layer reliability in cluster based network is greatly improved with the same power consumption.

Subsequently, T.E. Hunter and A. Nosratinia [62] 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.

Hsin Yi Shen and Shivkumar Kalyanaraman [63] 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. It was reported that cooperative system has larger capacity than direct transmission.

Subsequently, Hsin Yi Shen *et al.* [64] 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.* [65] 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 was evaluated. The BER and total energy consumption of the system is estimated and compared with other cooperative designs. 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.* [66] 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 [67] 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) [68] and directed diffusion [69] 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 is proposed by Fan Xiangning and Song Yulin [70] 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 this scheme provides significant energy savings and prolonged network lifetime over fixed clustering.

Moreover, MIMO techniques are incorporated in the cluster based sensor network to overcome the effects of channel fading and interference. Aitor del Coso *et al.* [71] 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. The proposed multihop scheme is effective to provide diversity equivalent to a MIMO system and significantly reduces the energy consumption with respect to the non-cooperative channel.

Zhong Zhou *et al.* [72] suggested a cooperative transmission scheme based on distributed space time block coding. The performance was 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. Also the optimal number of sensors in the cluster varies depending on Packet Error Rate (PER) requirements. However, 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.* [73, 74] 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 render uniform energy consumption in the network. The proposed communication architecture offers substantial energy savings in the wireless sensor network maintaining the required BER.

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.* [75] suggested a typical networking/communication protocol for WSNs i.e., LEACH to address asynchronous condition without loss of generality. LEACH protocol supports cooperative transmissions 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. The proposed 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.* [76] 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 are established using the devised energy consumption model. The suggested 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.* [77] 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. The proposed protocol has shown remarkable improvement in terms of energy efficiency and the network lifetime than traditional LEACH scheme.

Although Wenqing Cheng *et al.* [77] 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.* [78] 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. It was reported that the cooperative MIMO scheme can distribute the energy dissipation more evenly throughout the network and achieve higher energy efficiency.

Hui Tian *et al.* [79] proposed mathematical formulation for maximizing network lifetime in grid-based WSNs. The method of placing minimal number of sensor nodes to maximize the coverage area when the communication radius of the sensor node is not less than the sensing radius was presented. Wint Yi Poe and Jens B. Schmitt [80] investigated random (uniform random) and deterministic (a square grid and a pattern-based Tri-Hexagon Tiling (THT)) node deployments for large-scale WSNs, considering the performance metrics such as coverage, energy consumption, and message transfer delay. The formulated simple energy model proved that THT is a well performing node deployment strategy for WSN applications.

Subsequently, Jun Xiao [81] proposed a hexagonal grid-based sensor deployment algorithm, using the method of hexagonal grid plot and ant colony algorithm to deploy sensor nodes to the appropriate positions of wireless sensor network.

Y. Yu and V. K. Prasanna [82] proposed the use of modulation scaling over a multi-hop communication path to minimize the maximal energy consumption over all sensors along the path while satisfying a specific end-to-end latency constraint.

Bravos and Kanatas [83] evaluated different modulation schemes for sensor networks. However, attempts are not made to investigate on multi-hop nature of sensor nodes. Adaptive modulation techniques can be used to optimize the energy consumption caused by communicating under different conditions. Shuguang Cui *et al.* [84] investigated an adaptive modulation scheme for a point-to-point path loss AWGN channel considering circuit energy in the total energy budget to create a trade-off. Transmitting at a high rate requires more transmission power. However, shorter period of time is required to transmit the packet, thereby saving circuit energy, and vice versa.

Liang *et al.* [85] proposed a noncoherent FSK based modulation scheme which is suitable for implementation using low power integrated circuitry. The proposed scheme possesses adequate flexibility to support adaptive modulation and multiple simultaneous accesses. The FSK based modulation scheme proved to be potential to save energy by simplifying circuitry and allowing flexibility. Yu Yadong *et al.* [86] analyzed the impact of the coding and modulation on the transmission energy based on wireless channels modeled as a uniform distribution. Through adjusting channel coding and modulation mode in time according to the change of the quality of the wireless channel, the averages number of retransmission of package can be reduced to save the average power consumption of the radio.

Along with the competitive inclinations in various wireless scenarios, game-theoretic approaches to radio resource allocation have been attracted much attention. Substantial work has been done to solve the power control or spectrum sharing problem as a strategic and extensive game (cooperative [87, 88] or non-cooperative fashion [89-92] auction-based [93] and bargaining [94]), where simply the actions are imposed on each individual user (player).

Allen. B. MacKenzie and Stephen B. Wicker provided motivation for using game theory to study communication systems, and in particular power control [95]. The basic concepts of game theory and also the reason for using game theory as an appropriate tool for analyzing some communication problems have been addressed.

Zhu Han and K.J. Ray Liu modeled power control as a non-cooperative game in which users choose their transmit powers in order to maximize their utilities [96]. Subsequently, Farhad Meshkati *et al.* [97] proposed a game theoretic approach to energy-efficient power control in multi-carrier CDMA systems. Later, a game-theoretic approach to power control for wireless data networks in frequency selective multipath environments was proposed by Giacomo Bacci *et al*. [98].

A game-theoretic model has been proposed to study the cross-layer problem of joint power and rate control with QoS constraints in multiple-access networks [99]. The utility function considered here depends on both transmission rate and power and the existence of NE in the non-cooperative joint rate and power control game (NRPG) is studied. Farhad Meshkati, Andrea J. Goldsmith, H. Vincent Poor, and Stuart [100] propounded a game-theoretic framework to derive the best-response strategies and Nash equilibrium solution to study the effect of constellation size on the energy efficiency of wireless networks for M-QAM [83, 101] modulation. Using this framework, the tradeoffs among energy efficiency, delay, throughput and constellation size are quantified for a CDMA network [102,103]. These schemes are not capable of optimizing both the transmission rates and power to maximize spectral efficiency.

The research work done in the area of MIMO game is quite insignificant [104-109]. M. F. Demirkol and M. A. Ingram [104], S. Ye and R. S. Blum [105], C. Liang and K. R. Dandekar [106], considered the rate maximization game in MIMO interference channels and provided only numerical results to support the existence of a NE of the game. However, the uniqueness of the equilibrium and convergence of the proposed algorithms are not taken into consideration. Consequently, G. Arslan *et al.* [107], showed that the MIMO rate maximization game is a concave game, implying the existence of a NE for any set of arbitrary channel matrices. Subsequently, E. Larsson and E. Jorswieck focused on the competition and collaboration on the MISO interference channel, where only single output was considered [108]. Gesualdo Scutari *et al*. [110] proposed a game theory based competitive maximization of mutual information in noncooperative interfering networks in a fully distributed fashion. The proposed framework has also been generalized to the (square) MIMO case.

Wei Liu *et al.* [111] applied the NUM approach to the cooperative MIMO sensor network and jointly optimized the network utility and lifetime. Initially, energy consumption model and the link capacity restriction of cooperative MIMO transmission was analysed. Then, the primal optimization problem was solved by using the dual decomposition technique to propose a subgradient based distributed optimization algorithm. It has been established that, by using the distributed algorithm, the cooperative MIMO sensor network lifetime and utility can converge to Pareto optimal tradeoff values only with the requirement of neighbourhood price information exchange. Further, to regulate transmit-power and enhance the total throughput, Cheng shi-lun and Yang zhen [112] proposed a novel transmit-power control game (TPCG) algorithm and M-TPCG algorithm which combines adaptive modulation and transmit power control. It has been proved that TPCG algorithm can regulate their transmit powers and enhance the total throughput effectively, whereas M-TPCG algorithm can achieve maximal system throughput.

Further, Pau Closas *et al.* [114] addressed the issue of network topology control in WSN and proposed a fully distributed algorithm to adjust the transmission power of each node so as to make the network connected with an energy efficient solution. The algorithm proved to provide the probability of connectivity close to one for a relatively low node density. Subsequently, Hongliang Ren and Max Q. H. Meng [113] proposed a game theoretic modeling of joint topology control and power scheduling for wireless heterogeneous sensor networks. Three desirable characteristics such as reliability, connectivity and power efficiency are considered in designing the topology and power control game. A static complete-information game for power scheduling is formulated and the existence of NE is evaluated. Further, the outcome shows the ability to maintain reliable connectivity, reduced power consumption while achieving the desirable network performances. Gao Peng *et al.* [115] have proposed a non-cooperative power control game for AMC. However, the energy of the nodes has not been taken into consideration while designing the game.

Shamik Sengupta *et al.* [116] proposed a game theoretic framework for power control in WSN and found that Nash equilibrium exists, if minimum and maximum threshold are assumed for channel condition and power level, respectively. However, a node should transmit only when its channel condition is better than the minimum threshold and its transmission power level is below the threshold power level. Subsequently, Yujian Li *et al.* [117] proposed a game theoretic approach to joint modulation, rate and power control for cognitive CDMA communications. An adaptive utility function which links modulation (non-coherent frequency shift keying (NFSK) and binary phase shift keying (BPSK)), rate and power control is adopted. It was proved that each user changes its modulation to achieve higher performance according to its achievable rate. The nearer users select the full rate, NFSK and less power. However, farther users use full power, BPSK and less rate.

Selfish behaviour of nodes in wireless sensor networks may lead to socially undesirable equilibriums. So, incentive mechanisms were developed to force nodes to an optimal equilibrium and encourage participation. Incentive mechanism can be examined broadly in two categories such as credit exchange systems and reputation based systems based on their way of incentivizing nodes.

One of the techniques for nodes to behave in a way that is socially desirable is to adopt a mechanism of change and reward [118]. In this technique, nodes are rewarded with credit for participation and this credit is debited when requesting cooperation from other nodes. However, this method requires tamper proof hardware to prevent nodes from cheating during credit exchange. In addition, such techniques may be cumbersome to implement as charges and rewards are calculated on a per packet basis [119].

Another technique used for creating an incentive mechanism among nodes is to tag non participating nodes as misbehaving and to gradually isolate them from the network. Game theory has been used for the analysis of a reputation exchange mechanism [120]. According to this mechanism, a node assigns reputation values to its neighbours based on its direct interaction with them and on the indirect reputation information obtained from other nodes. This reputation mechanism is modeled as a repeated game among nodes. The analysis of this game aids in assessing the robustness of the reputation scheme against different node strategies and in deriving conditions for cooperation.

The introduction of an external centralized authority is another different approach for shifting to a desirable equilibrium [95]. Typically, the external authority evaluates the strategy that will lead to a system wide beneficial state and inform the nodes about it. It may also change the rules of the game dynamically to ensure optimality of the system. Such an algorithm is of limited applicability to a wireless sensor network because of the assumption of a central control. However, it may be possible to use an existing cluster head selection algorithm to select authorities as referees and thereby adapt this external equilibrium inducing mechanism to wireless sensor networks.

All the research work mainly focused on the application of game theoretic approach to power control problem and spectral efficiency in centralised networks. So far very little work has been done on the problem of applying game approach and pricing to distributed sensor networks to effectively handle the power control problem to maximize the network utility. However, in WSN, due to varying channel conditions, the measurements obtained are, in general, not accurate. Furthermore, it is also difficult to obtain the complete statistics of input traffic. As a result, the decision has to be based on the imprecision and uncertain measurements. To this end, game theoretic approach provides an approximate but effective means of describing the behaviour of the systems that are too complex and not easy to tackle mathematically [121-126]. It also provides a platform for handling uncertainty and imprecise knowledge. Having the nature of coping with uncertainty and imprecision problems, game theoretic approach is expected to provide a good solution to the power control and spectral efficiency scheme.

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. Several efforts have been made to overcome interference, radio irregularity and channel fading to improve the lifetime performance of the WSNs. Various power control schemes have been explored for 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.

However, attention has not been focused on the power control problem in WSN using game theoretic approach. Further incorporating ECC in the power control game and diversity schemes in MIMO based game 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 WSN by employing appropriate ECC, VMIMO schemes, proper node deployment scheme and AMC.

CHAPTER 3

POWER CONTROL GAME USING ECC

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 [6]. The resource constraint nature of these ultra small devices poses an immediate need for resource management. Generally energy is consumed only in operating radio circuitry and bit stream transmission at the physical layer. Energy consumed by the radio circuitry is fixed whereas the energy spent to transmit the data can vary based on channel loss, interference and transmission distance. The data transmitted from the sensor nodes is highly susceptible to error in a wireless environment which increases the transmit power. Proper power control algorithm is needed to minimize energy consumption during data transmission. So a power control solution using game theoretic approach with ECC is introduced to enhance the lifetime of the node by reducing the energy consumption in this chapter. The game with cost function or pricing is formulated as a utility maximizing power control game.

3.2 ERROR CONTROL CODING FOR WSN

In WSN, the communication channels are prone to channel impairments and errors are introduced during data transmission from the source to the destination. Error control coding which includes error detection and error correction ensures reliable delivery of data over these unreliable communication channels. Error detection allows detection of errors while error correction enables reconstruction of original data.

The three fundamental schemes of ECC used normally are Forward Error Correction (FEC), Automatic Repeat Request (ARQ) and Hybrid ARQ (HARQ) [127]. In FEC parity check bits are added to each transmitted message to form a codeword based on the code used by the system. A decoding error is committed if the receive node either fails to detect the presence of errors or fails to determine the exact location of the errors. In either case, an erroneous word is delivered to the receive node. When the receive node detects the presence of errors in a received word, it attempts to locate and correct the errors. After the error correction has been performed, the decoded word is then delivered to the destination.

The main problem encountered in a sensor network scenario is the fact that in most cases erroneous packets are completely destroyed due to synchronization problems between the sender and the receiver during the radio transmission. Because of these burst error, FEC would be advisable rather than ARQ. The main advantage with FEC is that there are no delays in message flows. Further, energy constrained transmission issue of WSN makes FEC a popular technique to be used in such networks compared to ARQ and HARQ [128-130].

Among the most popular FEC’s, Reed-Solomon (RS) codes are widely used in digital communication systems and storage devices because of its relatively simple decoder, which are also very appropriate for wireless sensor networks [131]. RS code is considered to be the best choice for WSN having maximum energy efficiency in proper channel conditions or when relay nodes are sufficient in numbers i.e. greater than five.

3.2.1 Reed Solomon Coding

Reed Solomon codes [127] are non binary cyclic error correcting codes. The original message is split in to fixed length blocks which is further sub divided into m-bit symbols. Each symbol is of fixed width, usually 3 to 8 bits wide. Since the power of RS code lies in being able to correct a symbol with all its bits in error, this code is more suitable for correcting burst errors.

RS code is generally represented as RS (n_{RS},k_{RS},d_{minRS}), and $d_{minRS}=n_{RS}-k_{RS+}1$

where

n_{RS} is the length of the code word

k_{RS} is the number of information symbols

d_{minRS} is the minimum hamming distance of the code

The code is capable of correcting any combination of t_{RS} errors and t_{RS} is given by

$$t_{RS} = \left\lfloor \frac{d_{minRS} - 1}{2} \right\rfloor \tag{3.1}$$

The RS coded bit error rate (BER) of QPSK modulation is expressed as

$$BER_{RS} \le \frac{2^{m-1}}{n_{RS}} \sum_{j=t_{RS}+1}^{n_{RS}} \frac{j + t_{RS}}{n_{RS}} \binom{n_{RS}}{j} p_c{}^{j} (1 - p_c)^{n_{RS}-j} \tag{3.2}$$

where

p_c is the coded symbol error probability

j is the number of errors in a block of n_{RS} symbols

3.2.2 Multivariate Interpolation Decoding RS Code

Since Bleichenbacher, Kiayias, and Yung (BKY) and Coppersmith and Sudan (CS) decoders of RS codes fail for certain error patterns, the Multivariate Interpolation Decoding RS (MIDRS) code was introduced by Parvesh and Vardy [132] to improve the error correcting capability. In MIDRS, M_n number of RS codes are transmitted together and decoded using (M+1) variate interpolation. This MID algorithm attempts to list-decode upto t_{MIDRS} errors, in RS code of length n_{RS} and rate R. This improves the decoding radius by a large margin especially for high rate codes.

The error-correcting capability t_{MIDRS} of the MID algorithm is given by,

$$t_{MIDRS} = M_n n_{RS} \left(1 - \frac{k_{RS}}{n_{RS}}^{\left(\frac{M_n}{M_n + 1} \right)} \right) \tag{3.3}$$

If n_{MIDRS} is the length of the code word for MIDRS, BER is calculated as

$$BER_{MIDRS} \leq \frac{2^{m-1}}{n_{MIDRS}} \sum_{j=t_{MIDRS}+1}^{n_{MIDRS}} \frac{j + t_{MIDRS}}{n_{MIDRS}} \binom{n_{MIDRS}}{j} p_c{}^{j} (1 - p_c)^{n_{MIDRS} - j} \tag{3.4}$$

Since the error-correcting capability t_{MIDRS} of the MID algorithm is greater than t_{RS} of RS codes for all rates, the energy efficiency of WSN is maximized. This ability of MIDRS to correct errors in the received sequence can provide better BER performance for the same SINR compared to RS coded system.

3.3 GAME THEORETIC APPROACH FOR POWER CONTROL

Formally, the game is defined as $G=[N, A_i, U_i]$ and has the following three components[15, 116]

The set of players, N = {1,2,3…,x}

The set of actions (strategy profile), A_i, available for a player ‘i’ to make a decision.

The payoff (utililty) function U_i resulting from the strategy profile.

The model considered for the analysis of the game consists of N homogeneous nodes in the sensor network. The players of the game are considered as nodes in WSN. The set of actions (strategies) available for the player 'i' to make a decision, consist of all possible power levels ranging from the minimum transmit power s_{min} to maximum transmit power s_{max}. The nodes in the network play repeated game. The game is played by having all the nodes simultaneously choosing their individual strategies. This set of choices results in the payoff (utility) of the game.

Each round in WSN consists of data collection phase, aggregation phase and transmission phase. The information available from previous rounds is used to work out strategies in future rounds. A source node with potentially as many neighbour nodes within the interference range is considered. The number of interfering nodes depends on the node density $\rho=N/A$, where A is the network area.

Since the nodes are considered as homogeneous, the actions allowed by the nodes are the same. All the nodes can transmit with any power level to make its transmission successful. If the nodes transmit with an arbitrary high power level, it will increase the interference level of the other nodes. To overcome the effect of this high interference, the neighbouring nodes in turn will transmit at higher power. This happens as a cascade effect and soon leads to a non-cooperative situation. To control this non cooperative behaviour, an equilibrium game strategy which imposes constraints on the nodes to act in cooperative manner even in a non-cooperative network is devised.

The existence of some strategy sets S_1, S_2, S_3 . . . , S_x for the nodes (1, 2, 3, . . , x) is assumed. In this game, if node 1 chooses its power level, $s_1 \in S_1$ and node 2 chooses its power level $s_2 \in S_2$, and so on, then the set of strategies chosen by all 'x' nodes is given by,

$$s = \{s_1, s_2, ...s_x\} \quad (3.5)$$

This vector of individual strategies is called a strategy profile. The set of all such strategy profiles is called the space of strategy profile S′.

At the end of an action, each node $i \in N$ receives a utility value as given by

$$u_i(s)=u_i(s_i, s_{-i}) \quad (3.6)$$

where

s_i is the strategy profile of the ith node

s_{-i} is the strategy profile of all the nodes but for the ith node

The utility of each node depends not only on the strategy it picked, but also on the strategies of the other nodes. In the power control game, each node maximizes its own utility in a distributed fashion. The transmit power that optimizes individual utility depends on transmit powers of all the other nodes in the system. It is necessary to characterize a set of powers where the players are satisfied with the utility. Such an operating point is called Nash Equilibrium (NE). At a NE, given the power levels of other players, no player can improve its utility level by making individual changes in its power.

The flow chart for the proposed game is given in Fig. 3.1.

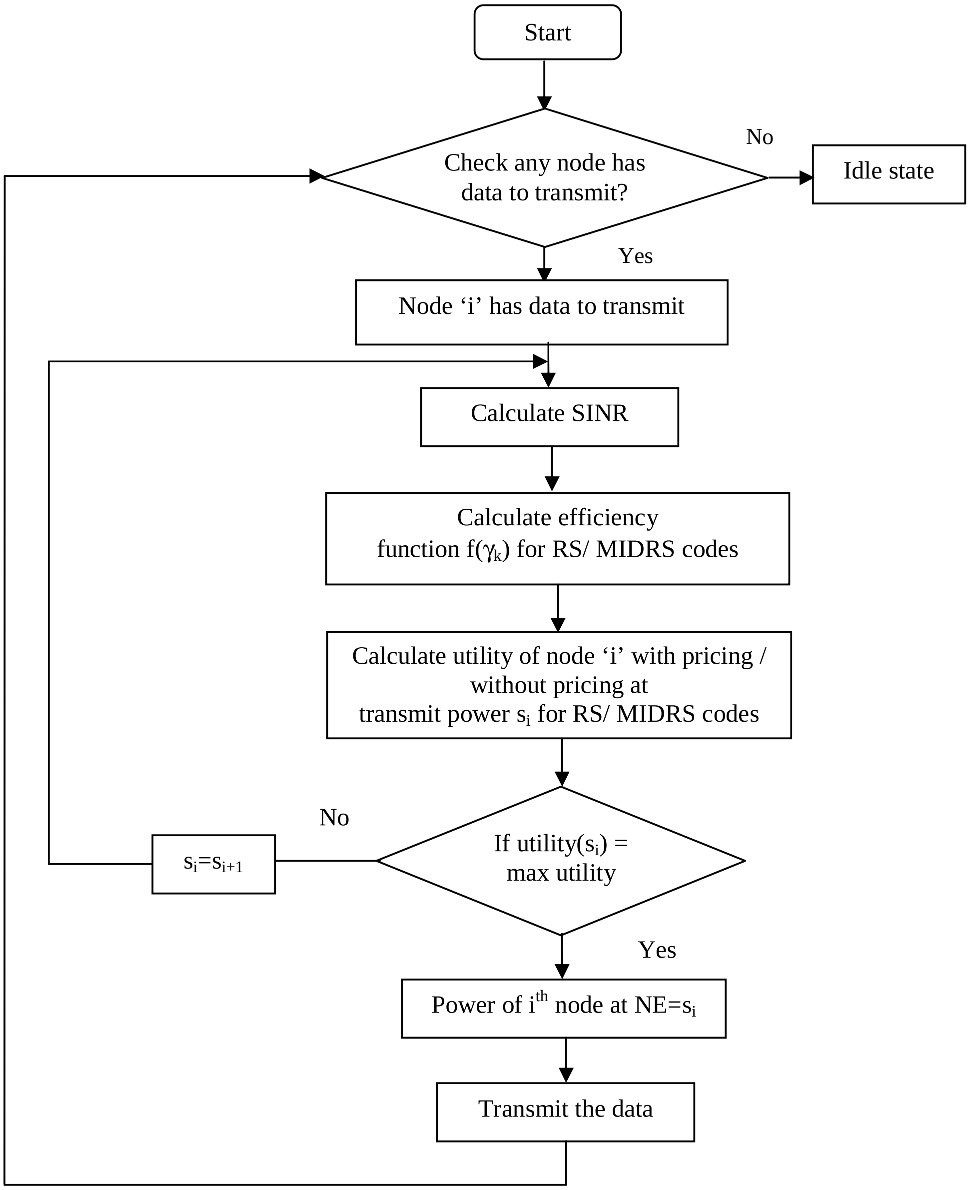


Fig.3.1. Flowchart of the power control game using ECC scheme

Consider node 'i' is transmitting data to node 'k'. The i^{th} node has control over its own power level s_i only.

The SINR of the i^{th} node is given as,

$$\mathrm{SINR}_i = \gamma_i = (\mathrm{PG})\frac{h_i s_i}{\sum_{k=1,k\neq i}^{N} h_k s_k + \sigma^2} \tag{3.7}$$

where,

PG is the processing gain given by

$$PG = \frac{W}{R} \tag{3.8}$$

W is channel bandwidth

R is data rate

s_i is the strategy profile (transmission power) of i^{th} node

s_k is the transmission power of k^{th} node

h_i is the path gain of node ‘i’

h_k is the path gain of node ‘k’

σ^2 is the noise spectral density

Based on the information available to a node ‘i’, such as its own power level, channel condition, and expected SINR of neighbouring receive nodes (which is obtained through periodic acknowledgment received), the utility function using FEC for this sensor node is formulated as given by

$$u_i(s_i, s_{-i}) = \frac{LR}{Fs_i}(f(\gamma_k)) \tag{3.9}$$

where

L is the number of information bits in a packet of size F bits

$f(\gamma_k)$ is the efficiency function

For RS code the efficiency function is expressed as

$$f(\gamma_k)_{RS} = (1-2BER_{RS})^F \tag{3.10}$$

For MIDRS code the efficiency function is modified as

$$f(\gamma_k)_{MIDRS} = (1-2BER_{MIDRS})^F \tag{3.11}$$

Substituting eqn. (3.10) in eqn.(3.9), the utility function of a node using RS code becomes

$$u_i(s_i,s_{-i})_{RS} = \frac{LR}{Fs_i}(1-2BER_{RS})^F \tag{3.12}$$

Substituting eqn. (3.11) in eqn. (3.9), the utility function of a node using MIDRS code becomes

$$u_i(s_i,s_{-i})_{MIDRS} = \frac{LR}{Fs_i}(1-2BER_{MIDRS})^F \tag{3.13}$$

The utility function is used to arrive at the optimal power at which the node should comply with to reach the NE.

3.3.1 Pricing of the Game with ECC

Although the NE provides a power control solution for the sensor node, it is not necessarily the best operating point for the whole system. That is, there exist other power solutions such as pricing [116, 123] to make the utilities of all the nodes greater than those at NE. The pricing function defines the instantaneous “price” a node pays for using a specific amount of power that causes interference in the system.

In a WSN each sensor node tries to maximize its own utility by adjusting its power optimally as given by the utility function. The utility of a sensor node depends on the interference it receives from other nodes, but it ignores its own interference in terms of drainage of energy. Pricing function is effective in regulating this externality. The pricing function accounts for the energy consumed/drained by the sensor nodes with usage of transmission power.

Generally three types of pricing functions such as linear, quadratic and exponential are considered. The pricing function should increase monotonically with the transmit power and should also be convex. Hence a simple linear pricing function which satisfies the above condition is chosen to understand the effect of pricing on the power control problem.

If the strategy of the ith node is to transmit at power $s_i \in S$, the pricing function is given as,

$$A(s_i)=cs_i \tag{3.14}$$

where c is the pricing factor.

Then the utility with pricing if a node is transmitting is given by

$$u_i(\text{pricing}) = u_i(s_i, s_{-i}) - A(s_i) \tag{3.15}$$

The concept of pricing provides the best operating point compared to the game without pricing.

3.3.2 Power Efficiency of the Game with ECC

In WSNs, since great importance is attached to the resource-constrained feature, power control should be performed in the direction of enhancing power efficiency, i.e., it is more important to maximize the number of bits that can be transmitted per Watt of power consumed rather than to maximize the throughput [133].

The probability of successful transmission of a packet containing F bits from node ‘i’ to node ‘k’ for RS code is given by

$$P_{RS} = (1 - BER_{RS})^F \tag{3.16}$$

The probability of successful transmission of a packet containing F bits from node ‘i’ to node ‘k’ for MIDRS code is given by

$$P_{MIDRS} = (1-BER_{MIDRS})^F \tag{3.17}$$

The power efficiency using the RS code is given by

$$\eta_{RS} = \frac{(1-BER_{RS})^F}{s_i} \tag{3.18}$$

The power efficiency using the MIDRS code is modified as

$$\eta_{MIDRS} = \frac{(1-BER_{MIDRS})^F}{s_i} \tag{3.19}$$

3.4 RESULTS AND DISCUSSION

The performances of the power control game using FECs such as RS code and MIDRS code for WSN are evaluated using MATLAB 7.0 in terms of utility, power efficiency and energy consumption. The parameters considered for the analysis of the power control game using FEC are summarised in Table 3.1.

Table 3.1 Simulation parameters for the power control game using ECC

Parameter	Value
Network area (A)	100×100m^2
Number of nodes (N)	100
Noise spectral density (σ^2)	-171dBm/Hz
Channel bandwidth (W)	1MHz
Data Rate (R)	20 kbps
Transmit power (s_i-s_{max})	(1-100)mW
Path loss component (h)	2
Length of the code word in RS code (n_{RS})	31 bytes
Number of information symbols in RS code (k_{RS})	29 bytes
Length of the code word in MIDRS code (n_{MIDRS})	62 bytes
Number of information symbols in MIDRS code (k_{MIDRS})	58 bytes
Modulation technique	QPSK
Number of encoders in MIDRS (M_n)	2

3.4.1 Utility of the Game with ECC

Fig.3.2 shows the utility of the transmitting node without pricing with increase of transmission power. As the transmission power increases the utility increases and at one particular value of transmission power s_i the maximum utility is attained and this point is called as the Nash Equilibrium point. Beyond this point, the utility decreases gradually. This figure serves as a guideline for calculating the desired transmitting power that maximises utility for the game using RS code and MIDRS code and without coding.

Without error control coding, a maximum utility of 4.346×10^5 bits/joule is achieved for a transmission power of 36mW. With RS coding the utility of 5.549×10^5 bits/joule is achieved for a transmission power of 28mW, whereas with MIDRS coding utility of 6.4×10^5 bits/joule is achieved for a minimum transmission power of 24mW. The increase in utility and decrease in transmission power of the game with MIDRS coding is due to the greater error-correction radius t_{MIDRS} of the MID algorithm.

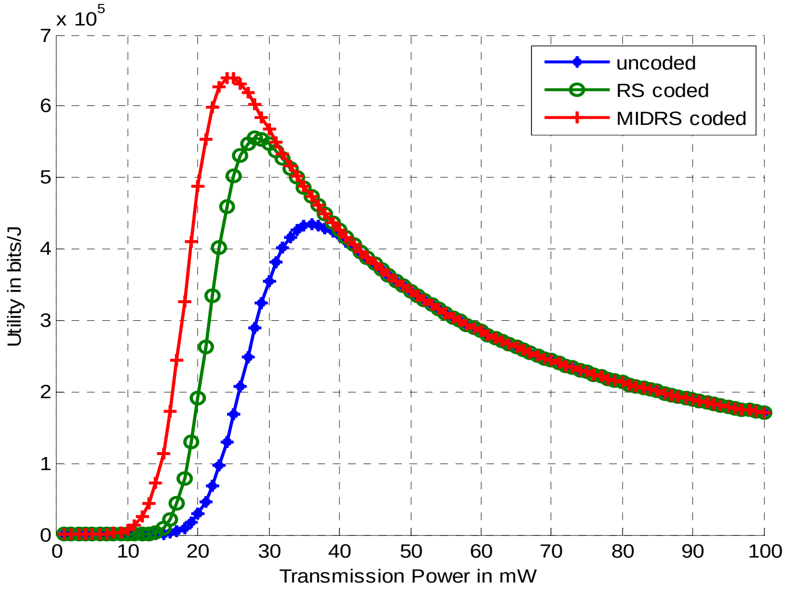


Fig.3.2. Utility of the game using ECC without pricing

Fig.3.3 elucidates the utility with pricing as a function of transmission power. It is discerned that, without ECC, a maximum utility of 4.706×10^5 bits/joule is achieved for a transmission power of 36mW, with RS coding an utility of 5.829×10^5 bits/joule is achieved for a transmission power of 28mW, whereas with MIDRS coding an utility of 6.65×10^5bits/joule is achieved for a transmission power of 24mW. By introducing the concept of pricing, the utility has been increased for the same amount of transmission power when compared to that of without pricing scheme. Increase in the system performance (utility) by 6% is established through pricing, by implicitly inducing cooperation and yet maintaining the non cooperative nature of the resulting power control solution.

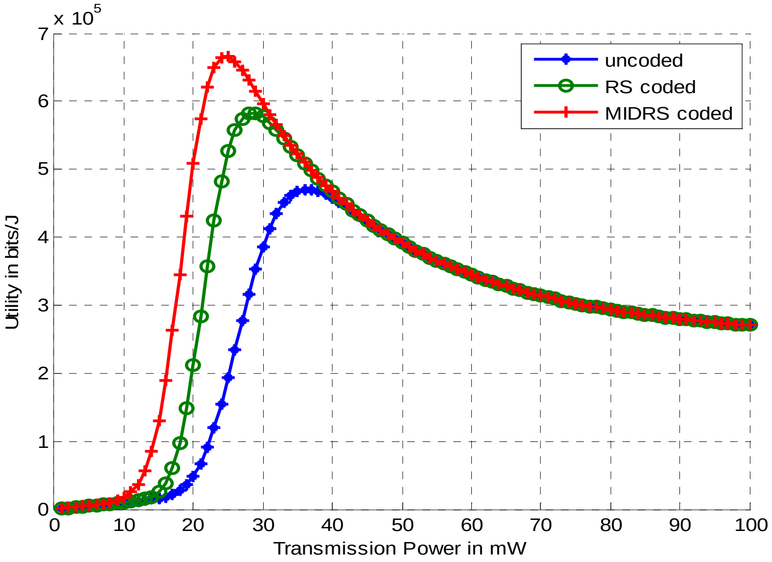


Fig.3.3. Utility of the game using ECC with pricing

3.4.2 Power Efficiency with ECC

From Fig.3.4 it is inferred that at high SINR increasing the transmitting power unnecessarily decreases the power efficiency below the maximum. Hence at high SINR, a node should transmit at low power to maximise its power efficiency. At low SINR the power efficiency is very low for all power levels and hence the node should not transmit under such worse channel conditions. It is also observed that RS and MIDRS codes provide an improvement in power by 31% and 43% respectively over uncoded scheme for a particular SINR value of 7dB.

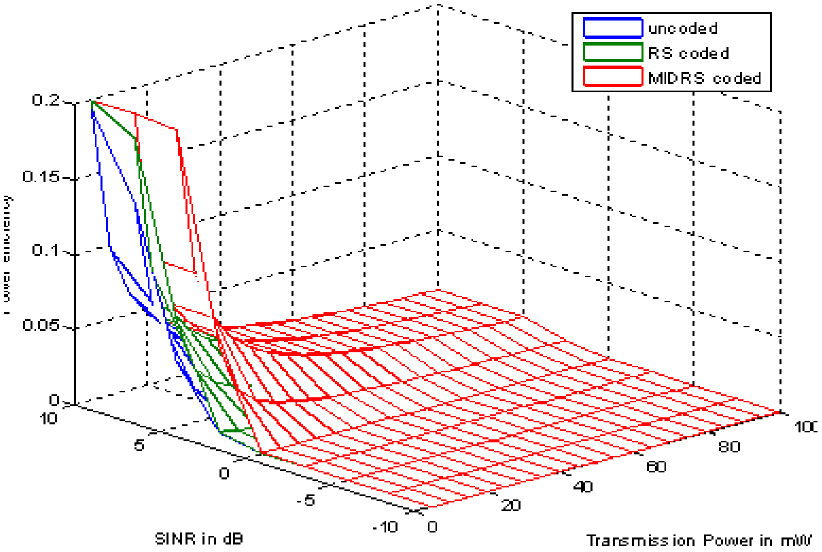


Fig.3.4. Power efficiency of the game with ECC

3.4.3 Energy Consumption with ECC

Fig.3.5 shows the variation of energy consumption with distance.

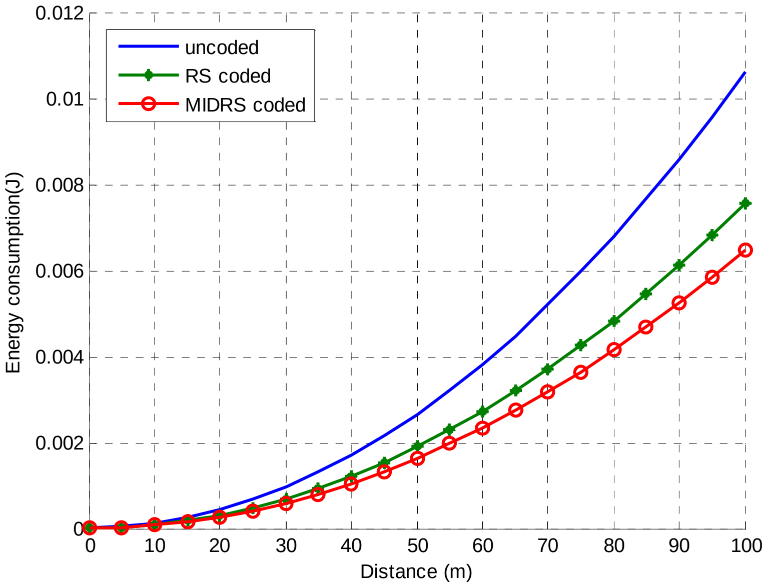


Fig.3.5. Energy consumption of the game with ECC

It is evident from this figure that, on considering a distance of 50m, the game with RS and MIDRS codes provide 28.6% and 38.7% decrease in energy consumption respectively. MIDRS provides 10% decrease in energy consumption compared to RS code.

3.5 SUMMARY

A game-theoretic approach with error control coding to solve the power control problem encountered in sensor networks is presented. The utility maximizing power control game is formulated and the existence and uniqueness of the Nash Equilibrium are studied. The utility, power efficiency and energy consumption of nodes employing RS codes and MIDRS codes are compared. The outcome shows that the proposed game with pricing employing MIDRS codes attains the best response for the sensor nodes by consuming less power. The reduction in transmit power is due to the error correcting code which allows the system to operate at significantly lower SINR than an uncoded system, for the same BER. Further, the game with pricing provides increase in utility by creating cooperation among the competent nodes.

CHAPTER 4

POWER CONTROL GAME WITH DEPLOYMENT SCHEMES

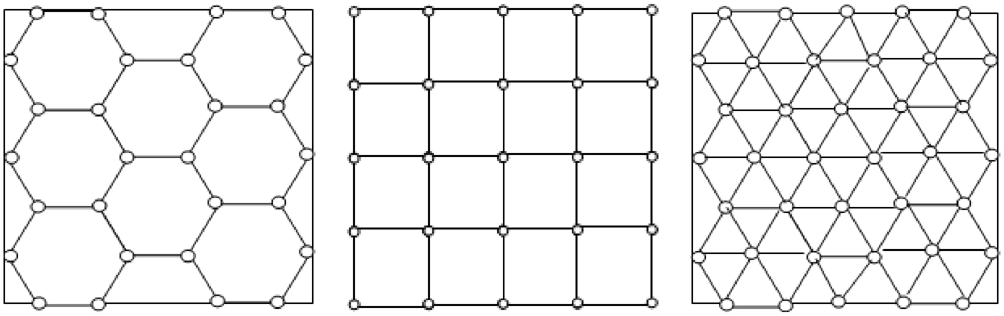
4.1 INTRODUCTION

Deployment of nodes in WSN is a challenging task due to its characteristics such as dynamically changing topology, lack of centralized authority and decentralized architecture. A proper node deployment scheme can lessen the complexity of problems like routing, data aggregation and communication in WSN. Moreover, it can extend the lifetime of WSNs by minimizing energy consumption [134]. A sensor network can be deployed either with deterministic placement, where a particular quality of service can be guaranteed; or with random placement, where sensors are scattered possibly from an aircraft. Although the random node deployment is preferable in many applications, it is currently infeasible in most situations as the individual sensors are generally too expensive for this level of redundancy. Hence other deployments should be investigated since an inappropriate node deployment can increase interference in the network. In this chapter, adjustment of transmission power of each node in a WSN considering the residual energy of the nodes for various deployment schemes is formulated as non cooperative game with and without pricing.

4.2 DEPLOYMENT STRATEGY

Sensing coverage is an important issue in WSN. The strategy of how to deploy sensor nodes in a large environment, will affect the utility of the network just like the quality of communication.

A rectangular area ‘A’ is taken for the deployment of the sensors. Random, square grids, triangular and hexagonal topology for the deployment of sensors as shown in Fig.4.1 are considered. The set of active nodes which are used for sensing the data and communicating at any time lies on the vertices of a regular polygon [135].



(a) Hexagonal topology (b) Square grid topology (c) Triangular topology

Fig. 4.1 Different regular network topologies

The number of nodes required for the random topology is given as

$\Pr[z_{min} \geq z] \equiv \Pr$[all nodes have at least z neighbours in the reception range]

$$= \left(1 - \sum_{n=0}^{z-1} \frac{(\rho a_R)^n}{n!} e^{-\rho a_R}\right)^N \tag{4.1}$$

where $a_R = \pi\ r_R^2$ is the area covered by the receiving range of a node and r_R is the receiving range of a node which is equal to the arm length of a regular polygon.

The number of active nodes required for the square grid topology is given as

$$N_{sqr} = \left\lfloor \left(\sqrt{3}(2M+1)\right) \big/ (2) + 1 \right\rfloor \left\lfloor \left((3M+1)\right) \big/ (2) + 1 \right\rfloor \tag{4.2}$$

where M is an integer

The number of active nodes required for the triangular topology is given as

$$\begin{aligned} N_{tri} = & \left\lfloor \left(\sqrt{3}(2M+1)\right) \big/ (2) + 1 \right\rfloor \left\lfloor \left((3M+1)\right) \big/ \left(2\sqrt{3}\right) + 1 \right\rfloor + \\ & \left\lfloor \left(\sqrt{3}(2M+1) - 1\right) \big/ (2) + 1 \right\rfloor \left\lfloor \left((3M+1)\right) - \sqrt{3} \big/ \left(2\sqrt{3}\right) + 1 \right\rfloor \end{aligned} \tag{4.3}$$

For the hexagonal topology the number of active nodes required is given by

$$N_{hex} = 2\left(M + 1\right)^2 \tag{4.4}$$

For M=4 the number of active nodes for the different regular topologies is calculated and is given in Table 4.1.

Table. 4.1 Number of active nodes for the different regular topologies

Random	**Square grid**	**Triangular**	**Hexagonal**
100	67	76	50

From the Table 4.1, it can be inferred that the hexagonal topology requires less number of active nodes compared to its counterparts, which inturn reduces the cost of the WSN. It is assumed that the receiving range of a node r_R is equal to the arm length of a regular polygon. The interference range is considered to be $r_I = \sqrt{5} r_R$. Within this interference range the number of interfering nodes for the various topologies is obtained for a given area [135] and it is found to be 5 nodes for hexagonal topology, 8 nodes for triangular topology, 10 nodes for square grid topology and around 22 nodes for random topology. The hexagonal deployment scheme with 50 nodes provides better performance compared to random deployment scheme, because of the less number of interfering nodes. Since the topology of the WSN changes with the depletion of battery resources; the power control should take into account the connectivity of the network topology. By considering the node's residual energy, the nodes with minimum residual energy are used less frequently, thus prolonging lifetime of the node and hence the network.

4.3 GAME THEORETIC MODELLING

The game is an interactive decision making process between a set of self-interested nodes. At the beginning of the game, i^{th} node broadcasts a HELLO message at maximum transmission power to its nearest neighbour nodes. The neighbour nodes that have received the HELLO message from i^{th} node, calculate the minimal transmission power with which it can be reached and sends back an ACK message. Upon receiving ACK messages ith node gathers neighbours information.

Then the sensor node in WSN communicates with other node only when it is within its communication range. Thus it is possible to control the transmission range of the individual node thereby ensuring effective power control and coverage.

4.3.1 Power Control Algorithm with Residual Energy Check

The model considered for the analysis of the game consists of N homogeneous active nodes in the sensor network [114]. The number of active nodes for each topology is given in Table 4.1. The game is an iterative procedure and all the nodes play a repeated game. The game is played by all the nodes concurrently picking their individual strategies. This set of choices results in the payoff (utility) of the game.

After every iteration, the power level change of a node influences the overall topology of the network which is taken into account by the other nodes when optimizing their utility function. The game considers the energy of the nodes and connectivity of the network to estimate the optimal power needed for transmission of data from the source to the sink.

Consider node ‘i' is transmitting data to the sink node. Node ‘i' receives the sum of interference power $\sum_{k=1,k\neq i}^{N} h_k s_k$ from sink node. The SINR of the ith node (γ_i) considering the residual energy is given as,

$$\gamma_i = (PG)\frac{h_i s_i \frac{E_m}{E_{ir}}}{\sum_{k=1,k\neq i}^{N} h_k s_k \frac{E_m}{E_{kr}} + \sigma^2} \tag{4.5}$$

where,

E_{ir} is residual energy of the ith node

E_{kr} is residual energy of the kth node

E_m is the maximum energy of the node

The residual energy E_{kr} of the kth node is the difference between the maximum energy of the node and the energy consumption in the previous round. In order to achieve a NE in the strategic non-cooperative game, nodes iteratively decide its transmission power level by maximizing its utility function. This utility function is very important in non-cooperative power control game.

The utility of the ith transmitting node is given by,

$$u_i\left(s_i, s_{-i}\right) = \frac{LR}{Fs_i}(1-2BER)^F \tag{4.6}$$

The BER considering QPSK modulation is given as

$$BER = \frac{1}{b}\operatorname{erfc}\left(\sqrt{b\gamma}\sin\left(\frac{\pi}{m_0}\right)\right) \tag{4.7}$$

where

b is the number of bits per symbol

m_0 is the modulation order

The pricing function while considering residual energy is formulated as

$$A_R(s_i) = cRs_i\frac{E_m}{E_{ir}} \tag{4.8}$$

The utility of the ith node with the pricing function included is given by,

$$u_i\left(\text{pricing}\right) = \frac{LR}{Fs_i}(1-2BER)^F - A_R(s_i) \tag{4.9}$$

If the pricing function is a convex function of the node's power, and the utility function is a concave function of the nodes power, then the difference is concave, which proves the existence of a fixed point [15].

The transmitted power of the ith node is obtained

$$s_i = \arg\max_{s_i \in S_i} \left\{ u_i \left(s_i, s_{-i} \right) \right\} \tag{4.10}$$

Consider square grid deployment scheme in which the active nodes are placed on the vertices of the square grid. If any node has data to sent, then the network connectivity is monitored. If the network is connected the residual energy of the node is checked and the number of interfering nodes for each deployment scheme is calculated. The utility of the transmitting node is calculated depending on the residual energy and the deployment scheme.

The power at which maximum utility is obtained is the NE point. The nodes comply with the power at which NE is obtained and transmit the data with that optimal power. The same process is undertaken for the other deployment schemes.

4.3.2 Existence of Nash Equilibrium for the Proposed Game

For all $i \in N$ and $s_i \in S$, $u_i(s_i, s_{-i}) \geq u_i(s_i^*, s_{-i})$, then the power vector S is the Nash equilibrium of the power control game G. A NE point exists in the game if the power strategy S_i is a non-empty, convex and compact subset of some Euclidean space and $u_i(s)$ is continuous in S and quasi-concave in s_i.

Differentiating the equation (4.5) with respect to s_i

$$\frac{\partial \gamma_i}{\partial s_i} = f\left(\gamma_i\right) = \frac{W}{R} \frac{h_i \frac{E_m}{E_i}}{\sum_{k=1, k \neq i}^{N} h_k s_k \frac{E_m}{E_k} + \sigma^2} \tag{4.11}$$

Differentiating the equation (4.6) with respect to s_i

$$\frac{\partial u_i\left(s_i, s_{-i}\right)}{\partial s_i} = -\frac{LR}{Fs_i^2}\left(1-e^{-\gamma_i}\right)^F - cR\frac{E_m}{E_i} + \frac{LR}{s_i}\left(1-e^{-\gamma_i}\right)^{F-1} e^{-\gamma_i} f\left(\gamma_i\right)$$

Taking the second-order derivative of $u_i\left(s_i, s_{-i}\right)$ with respect to s_i yields

$$\frac{\partial^2 u_i\left(s_i, s_{-i}\right)}{\partial {s_i}^2} < 0$$

Since $\frac{\partial^2 u_i\left(s_i, s_{-i}\right)}{\partial {s_i}^2} < 0$, $u_i\left(s_i, s_{-i}\right)$ is concave in s_i. This proves that NE exists in the game with pricing and they are Pareto superior [15] compared to the equilibrium of the game without pricing.

4.4 RESULTS AND DISCUSSION

The random, square, triangular and hexagonal topologies along with residual energy check were considered to determine the deployment scheme that provides better connectivity and power control. The performances of the proposed game are evaluated using MATLAB 7.0 in terms of utility, energy consumption and network lifetime. The simulation parameters used are listed in Table 4.2.

Table 4.2 Simulation parameters for various deployment schemes

Parameter	**Value**
Network area (A)	100×100m^2
Number of nodes for random topology	100
Number of nodes for square grid topology	67
Number of nodes for triangular topology	76
Number of nodes for hexagonal topology	50
Maximum energy of a node	5J
Modulation	QPSK

4.4.1 Utility for Various Deployment Schemes

The utility as a function of transmit power for all the four deployment schemes, without residual energy check is shown in Fig.4.2.

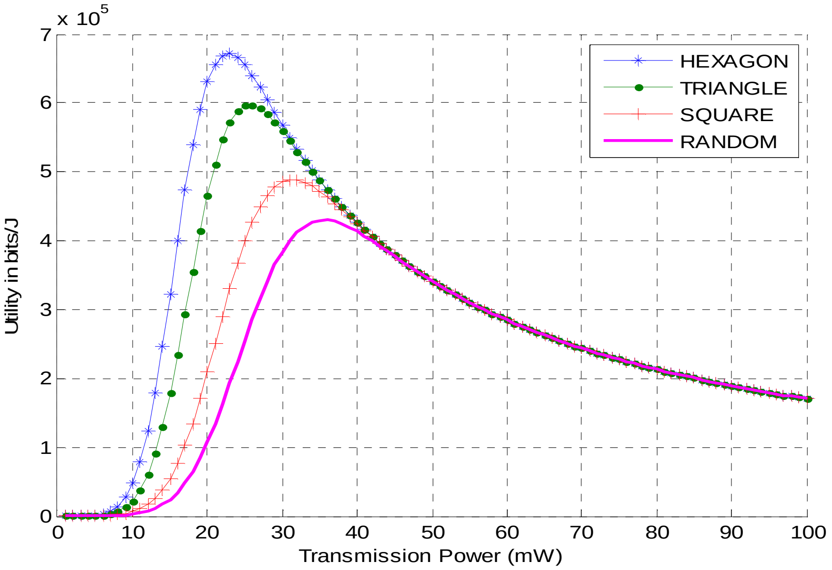


Fig.4.2. Utility of the game without pricing without residual energy check

The random, square and triangular deployment schemes provide the maximum utility of 4.346×10^5 bits/joule, 4.88×10^5 bits/joule and 5.97×10^5 bits/joule at transmission power of 36, 32 and 26mW respectively. A maximum utility of 6.718×10^5 bits/joule is achieved at the minimum transmission power of 23mW for hexagonal deployment scheme. Hexagonal deployment provides 37% increase in utility and 28% reduction in transmission power as compared to square grid deployment and also provides 12.52% increase in utility and 11.5% reduction in power when compared with triangular deployment scheme. This is due to the less number of interfering nodes in hexagonal deployment scheme.

Pricing encourage the sensors to use resources more effectively. If a particular node in the network tends to increase its transmit power, it creates interference to the other nodes. The effect of pricing decreases the utility of that node by pricing factor $A_R(s_i)$ and increases the utility of the other nodes by pricing factor $A_R(s_i)$.

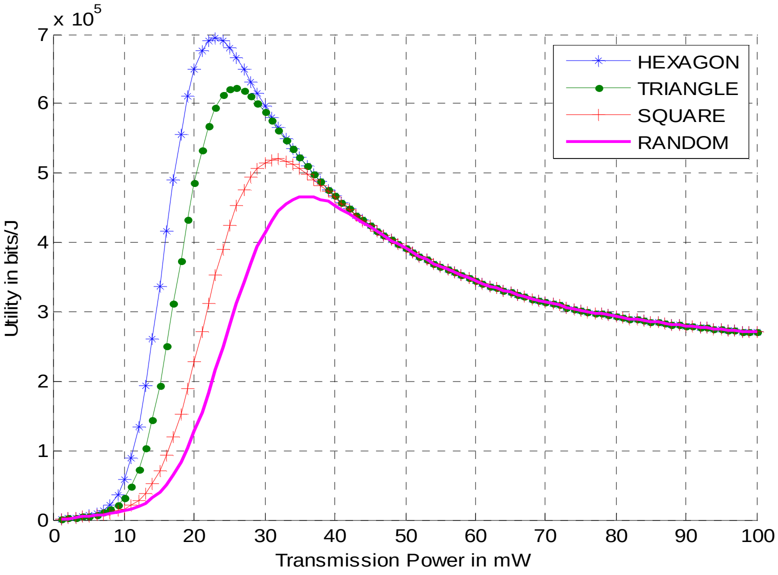


Fig.4.3. Utility of the game with pricing without residual energy check

From Fig.4.3 it is inferred that, hexagonal deployment scheme with pricing provides a maximum utility of 6.948×10^5 bits/joule at the transmission power of 23mW. An increase in utility by 3.4% is obtained by considering the pricing strategy.

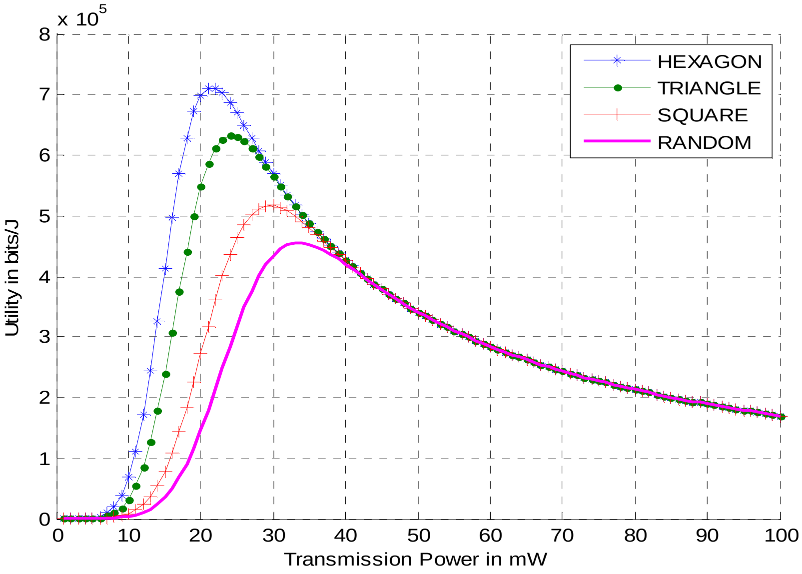


Fig.4.4. Utility of the game without pricing with residual energy check

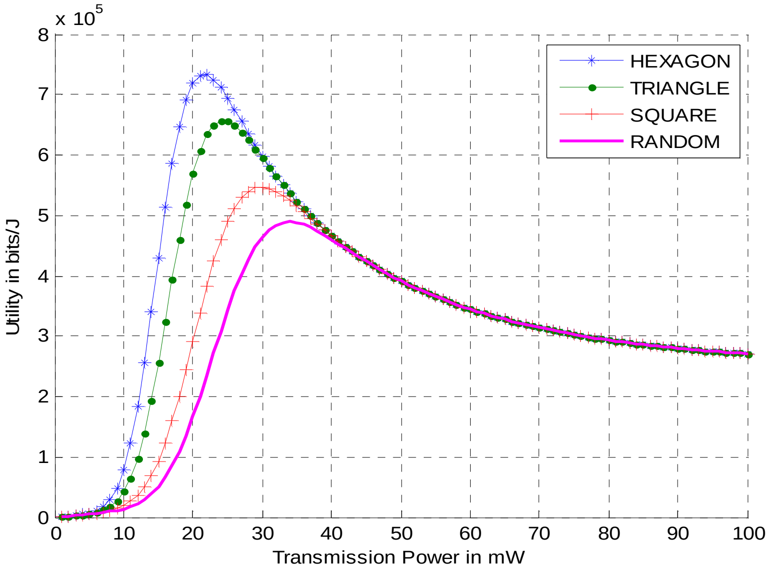


Fig.4.5. Utility of the game with pricing with residual energy check

The utility of the game considering residual energy of the node is given in Fig.4.4. The energy check algorithm effectively reduces total transmitting power of nodes. Hexagonal deployment provides maximum utility compared to other deployment schemes. For the hexagonal deployment with residual energy check a maximum utility of 7.104×10^5 bits/joule is achieved for a transmission power of 22mW.

From Fig.4.5 it is observed that the maximum utility and minimum transmission power are achieved by the hexagonal deployment scheme when compared to triangular and square grid deployment schemes. It is also observed that the hexagonal deployment with residual energy check and pricing achieves the maximum utility of 7.324×10^5 bits/joule for the minimum transmission power of 22mW.

4.4.2 Energy Consumption for Various Deployment Schemes

The energy consumption of various deployment schemes are presented in Fig.4.6.

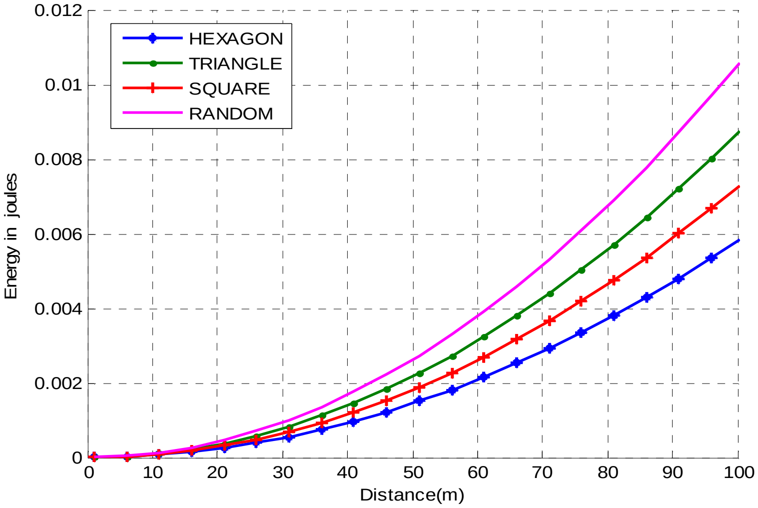


Fig.4.6. Energy consumption for various deployment schemes

When comparing the performance of the hexagonal deployment with the other schemes it is observed that there is a significant reduction in energy consumption because of less number of affected groups. Hence dividing the sensor field into hexagonal grids ensures better power control.

4.4.3 Lifetime Analysis of Hexagonal Deployment Scheme

Fig.4.7. explains the impact of transmission distance on lifetime of the node.

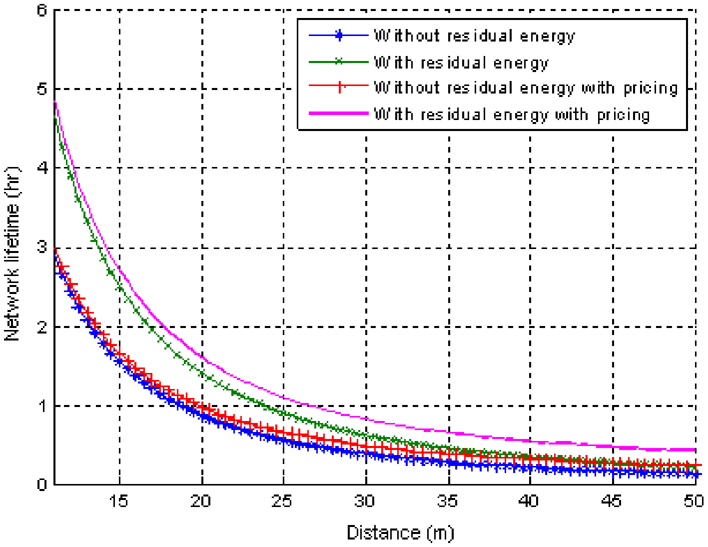


Fig.4.7. Lifetime analysis of hexagonal deployment scheme

From this figure it is noted that the residual energy check scheme enhances the lifetime approximately 55% and 66% for the distance of 20m and 35m respectively when compared to that of without residual energy check scheme. It is also inferred that lifetime of WSN with residual energy check scheme and pricing increases approximately 14% and 40% than that of residual energy check scheme without pricing for the same distances considered.

4.5 SUMMARY

A game theoretic model with pricing for power control taking into account the residual energy of the nodes in a sensor network considering various deployment schemes have been analysed in this chapter. The connectivity is taken into consideration and the existence and uniqueness of the NE are studied for the game model. The utility of nodes without residual energy check and with residual energy check are compared for all the deployment schemes. The maximum utility is obtained at minimal transmission power for hexagonal deployment scheme. With the inclusion of pricing the interference among the nodes due to the optimizing behavior of a particular node is suppressed. Further the outcome shows that employing residual energy check with pricing achieves the best response for the sensor nodes by requiring lesser transmit power and thereby extend the network lifetime efficiently.

CHAPTER 5

POWER CONTROL GAME USING VMIMO

5.1 INTRODUCTION

Wireless sensor network requires robust and efficient communication protocols to save energy and enhance network lifetime. However the adverse impacts caused by radio irregularities and fading increase the energy consumption and thereby reduces the WSN lifetime. To reduce the fading effects and to improve the energy efficiency in wireless channel, MIMO scheme is utilised for sensor network [46-52]. The lifetime of WSN can further be maximized by employing appropriate power control solution. The power control problem in VMIMO WSN is modeled as a coalitional game to select the cooperative nodes for enabling packet transmission and obtain better utility by forming groups and controlling the power cooperatively rather than individually. The cooperative sensors are dynamically selected based on the residual energy of the sensors and its geographical location, to reduce the overall energy consumption.

5.2 SYSTEM MODEL

In cluster based WSN the nodes are grouped into clusters with each cluster having a Cluster Head (CH) node to transmit the sensed data to sink. To route the sensed data from the cluster head to the destination, Low Energy Adaptive Clustering Hierarchy (LEACH) [53] an application-specific protocol architecture is exploited. In LEACH protocol, the cluster head is selected based on the residual energy of the node in the cluster, thereby the node which has more energy than other nodes and has not been cluster head previously becomes a cluster head. The operation of LEACH protocol is divided into rounds. 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.

Multipath fading and radio irregularities pose a big challenge for energy constraint WSN. To mitigate the multipath effects, antenna diversity has been proven to be effective. Diversity can be leveraged in the network, link or physical layers to provide reliable transmission with low power, reduce energy consumption and extend battery lifetime. However applying multiple antennas directly to a sensor network is impractical because of limited size of a sensor node which usually supports a single antenna. Cooperative MIMO schemes have been proposed [73-79] for WSNs to improve its performance.

The cooperative MIMO system model 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.

5.3 BASIC MIMO SYSTEM

A typical MIMO system consists of M_t transmitters and M_r receivers communicating over a wireless channel as shown in Fig. 5.1.

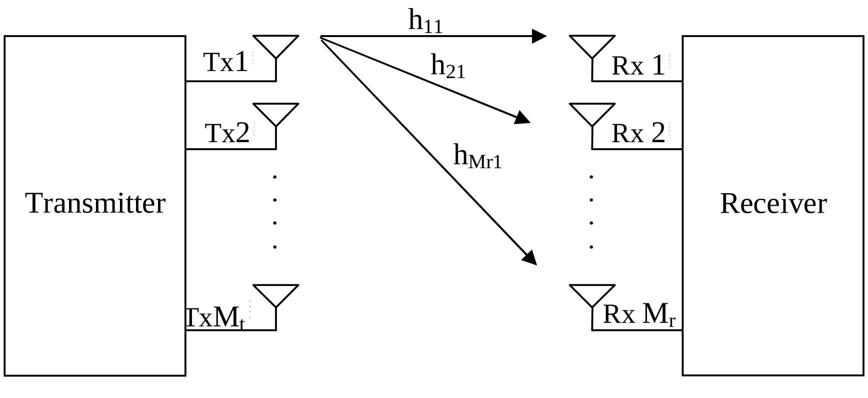


Fig. 5.1. Typical MIMO system model

Let h_{ij} be a complex number corresponding to the channel gain between transmit antenna j and receive antenna i.

The received signal vector y is expressed in matrix form as

$$y = HG_T + n \tag{5.1}$$

where

H is the MIMO channel matrix,

G_T is the transmit symbol vector

n is the additive noise vector.

To improve the performance of MIMO WSN, space time coding schemes are generally used. The space time codes provide the full diversity over fading channels and improve the quality of signal transmission. Of the space time coding schemes, STBC is more suitable [55, 75] for WSN with low encoder/decoder complexity.

5.4 SPACE TIME BLOCK CODE

Space time block code operates on a block of input symbols producing a matrix output whose column represent time and rows represent antennas [28]. It is defined by an ($M_t \times T_{bc}$) transmission matrix Y**,** where T_{bc} represents the number of time periods for transmission of one block of coded symbols [57]. The encoder structure of STBC is shown in Fig.5.2.

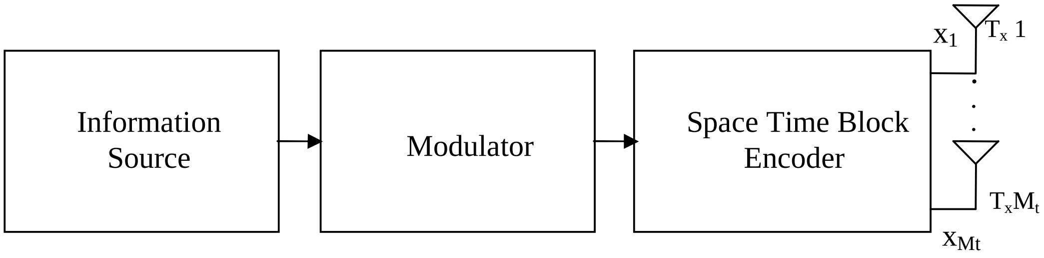


Fig.5.2. Encoder for STBC

At each encoding operation, a block of ‘m’ information bits are mapped into the signal constellation (2^m) to select ‘q’ modulated signals $x_1, x_2, ..., x_q$, where each group of m bits selects a constellation signal. The ‘q’ modulated signals are then encoded to generate M_t parallel signal sequences according to the STBC transmission matrix Y.

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

In case of M_t =2, 3, 4 transmit cooperative nodes, the STBC transmission matrix Y_2^*, Y_3^*, Y_4^* are used and are defined by

$$Y_2^* = \begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{pmatrix} \tag{5.2}$$

$$Y_3^* = \begin{pmatrix} x_1 & -x_2 & -x_3 & -x_4 & x_1^* & -x_2^* & -x_3^* & -x_4^* \\ x_2 & x_1 & x_4 & -x_3 & x_2^* & x_1^* & x_4^* & -x_3^* \\ x_3 & -x_4 & x_1 & x_2 & x_3^* & -x_4^* & x_1^* & x_2^* \end{pmatrix} \tag{5.3}$$

$$Y_4^* = \begin{pmatrix} x_1 & -x_2 & -x_3 & -x_4 & x_1^* & -x_2^* & -x_3^* & -x_4^* \\ x_2 & x_1 & x_4 & -x_3 & x_2^* & x_1^* & x_4^* & -x_3^* \\ x_3 & -x_4 & x_1 & x_2 & x_3^* & -x_4^* & x_1^* & x_2^* \\ x_4 & x_3 & -x_2 & x_1 & x_4^* & x_3^* & -x_2^* & x_1^* \end{pmatrix} \tag{5.4}$$

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

$$Y.Y^H = a(|x_1|^2 + |x_2|^2 + ... + |x_q|^2) I_{M_t} \tag{5.5}$$

where

Y^H is the Hermitian of Y

a is the constant

I_{M_t} is an(M_t x M_t) identity matrix

When $\mathbf{x}_i = (x_{i,1}, x_{i,2}, ..., x_{i,Tbc})$ is the transmitted sequence from the ith cooperative node and $\mathbf{x}_j = (x_{j,1}, x_{j,2}, \ldots, x_{j,Tbc})$ 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

$$\mathbf{x}_i \cdot \mathbf{x}_j = \sum_{t=1}^{T_{bc}} x_{i,t} . x_{j,t}^{*} = 0 , \quad i \neq j,\ i, j \in \{1, 2, ..., M_t\} \tag{5.6}$$

The inner product of the sequences enables the orthogonality for a given number of transmit cooperative nodes.

5.5 GAME FORMULATION

The game is formulated such that it allows dynamic formation of coalitions among sensor nodes while maximising their utilities with pricing. The game consists of two phases. First phase is the coalition formation game in which the cooperative nodes are selected for MIMO communication. The power control game is the second phase in which the cooperative nodes run a distributed power control algorithm that maximizes the utility at an optimal power. The cooperative nodes should comply with this power to reach the NE.

5.5.1 Coalition Formation Game

The selection of cooperative nodes which take part in MIMO communication is modeled as a coalitional game [136, 137] and coalition is done based on the distance and residual energy of the nodes. If a particular node in the network is frequently used for sensing and transmitting information, then the battery of that node will be depleted fast. This makes the sensor nodes unusable for critical applications such as environmental monitoring, military applications, precision agriculture etc. To prevent a node from becoming dead soon, the residual energy checking is done. The transmit power of the node is varied in accordance with the residual energy of the node. This conserves the energy of the node and prevents it from getting depleted soon and prolongs the lifetime of the node and that of the network.

The coalitional game is modeled as (N, υ, V)

where

N is the set of players (nodes), {1,2…..,x}

υ is the characteristic function based on the network lifetime.

V is the partition of N, V$\subseteq$ N.

Characteristic function of the system is modeled based on the network lifetime and is given by

$$\upsilon\left(V_j\right)=\left\{u^{v_j} \in R^{|v_j|} \middle| u_i^{v_j}=T_{net}, \forall i \in V_j\right\} \tag{5.7}$$

where

$u_i^{v_j}$ is the utility of the node within the coalition V_j

$|V_j|$ is the number of sensor nodes in V_j

T_{net} is the network lifetime

The network lifetime is the period of time from the network initialisation to the point when the first node runs out of energy and is given as,

$$T_{net} = \min\left\{T_{co1}, T_{co2}, .., T_{non\text{-}co1}, T_{non\text{-}co2}, ..\right\} \tag{5.8}$$

The lifetime of the sensor node which based on the residual energy of the node E_0 is given by

$$T_{co} = \frac{E_0}{s_i} \tag{5.9}$$

If E_i is the initial energy of the node and E_t is the energy consumption of the node in the previous round, the residual energy of the node is

$$E_0 = E_i - E_t \tag{5.10}$$

For the remaining nodes which do not take part in MIMO data communication, the energy consumption is assumed to be negligible and its lifetime is infinite.

Merge and split algorithm is used in the coalition formation game. During the coalition formation, the nodes form coalitions through an iteration of arbitrary merge and split rules repeated until termination.

Merge and split algorithm

Step 1 : All the active cluster nodes in the cluster are considered to form the coalition.

Step 2 : A collection of coalitions $V = \{V_1, ..., V_k\}$ is formed by the mutually disjoint coalition V_i taken from the M_t active nodes in the cluster.

Step 3 : An iteration of merge and split operation is repeated to achieve the characteristic function defined in equation (5.7)

Merge rule: Any set of coalitions $V = \{V_1, ..., V_l\}$ is merged if $\upsilon\left(U_{j=1}^{l} V_j\right) > \sum_{j=1}^{l} \upsilon\left(V_j\right)$; thus $\{V_1, ..., V_l\} \rightarrow U_{j=1}^{l} V_j$.

Split rule: Any set of coalition $U_{j=1}^{l} V_j$ is split if $\upsilon\left(U_{j=1}^{l} V_j\right) < \sum_{j=1}^{l} \upsilon\left(V_j\right)$; thus $U_{j=1}^{l} V_j \rightarrow \{V_1, ..., V_l\}$.

Step 4 : The iteration ends by a final merged coalition $\overline{V}$ composed of the cluster head and none or several cluster nodes.

A group of coalitions (nodes) decides to merge if it is able to improve its total utility through the merge; while a coalition splits into smaller coalitions if it is able to improve the total utility.

5.5.2 Utility Formulation for VMIMO WSN

Generally the utility function is defined as throughput (T) per transmit power of node and it is expressed for ith node as

$$u_i^{v_j}\left(s_i, s_{-i}\right) = \frac{T}{s_i} \tag{5.11}$$

The per-node throughput, in bits per second Hertz, of MIMO WSN is the sum of the normalized throughputs of the min (M_t, M_r) decoupled sub channels. Then the throughput of ith node is given as

$$T_i^{v_j}\left(s_i, s_{-i}\right) = \sum_{k=1}^{M_r} \frac{LR_k}{F}\left(f\left(\gamma_k\right)\right) \tag{5.12}$$

The overall power consumption to transmit the data using cooperative communication is modified as

$$s_{i(MIMO)} = \sum_{i=1}^{\min(M_t, M_r)} \frac{s_i}{\min\left(M_t, M_r\right)} \tag{5.13}$$

Hence the utility of the ith transmitting node using MIMO communication in WSN is obtained as

$$u_i^{v_j}\left(s_i, s_{-i}\right) = \sum_{k=1}^{M_r} \frac{LR_k}{F \sum_{i=1}^{\min(M_t, M_r)} \frac{s_i}{\min\left(M_t, M_r\right)}}\left(f\left(\gamma_k\right)\right) \tag{5.14}$$

5.5.3 Pricing Formulation for VMIMO WSN

The utility function with pricing for power control game using VMIMO is expressed as

$$u_i^{v_j}(\text{pricing}) = u_i^{v_j}(s_i, s_{-i}) - A^{v_j}(s_i) \tag{5.15}$$

where

$$A^{v_j}(s_i) = c\sum_{i=1}^{\min(M_t, M_r)} \frac{s_i}{\min(M_t, M_r)} \tag{5.16}$$

5.5.4 Power Efficiency of VMIMO WSN

The power efficiency considering in VMIMO WSN is given as

$$\eta_{\text{VMIMO}} = \frac{(1-\text{BER})^F}{\frac{s_i}{\min(M_t, M_r)}} \tag{5.17}$$

Consider node 'i' has data to transmit to node 'k'. The ith node then selects the cooperative nodes for communication based on the distance and residual energy using the coalitional game. Then it runs a non cooperative power control game to decide on the optimal power at which the cooperative nodes should abide by to reach the NE. The node 'i'along with the cooperative nodes transmit the data to receiving cooperative nodes. The receiving cooperative nodes then transmit the data to the node 'k' using this optimal power.

The flowchart of the proposed game is given below in Fig.5.3.

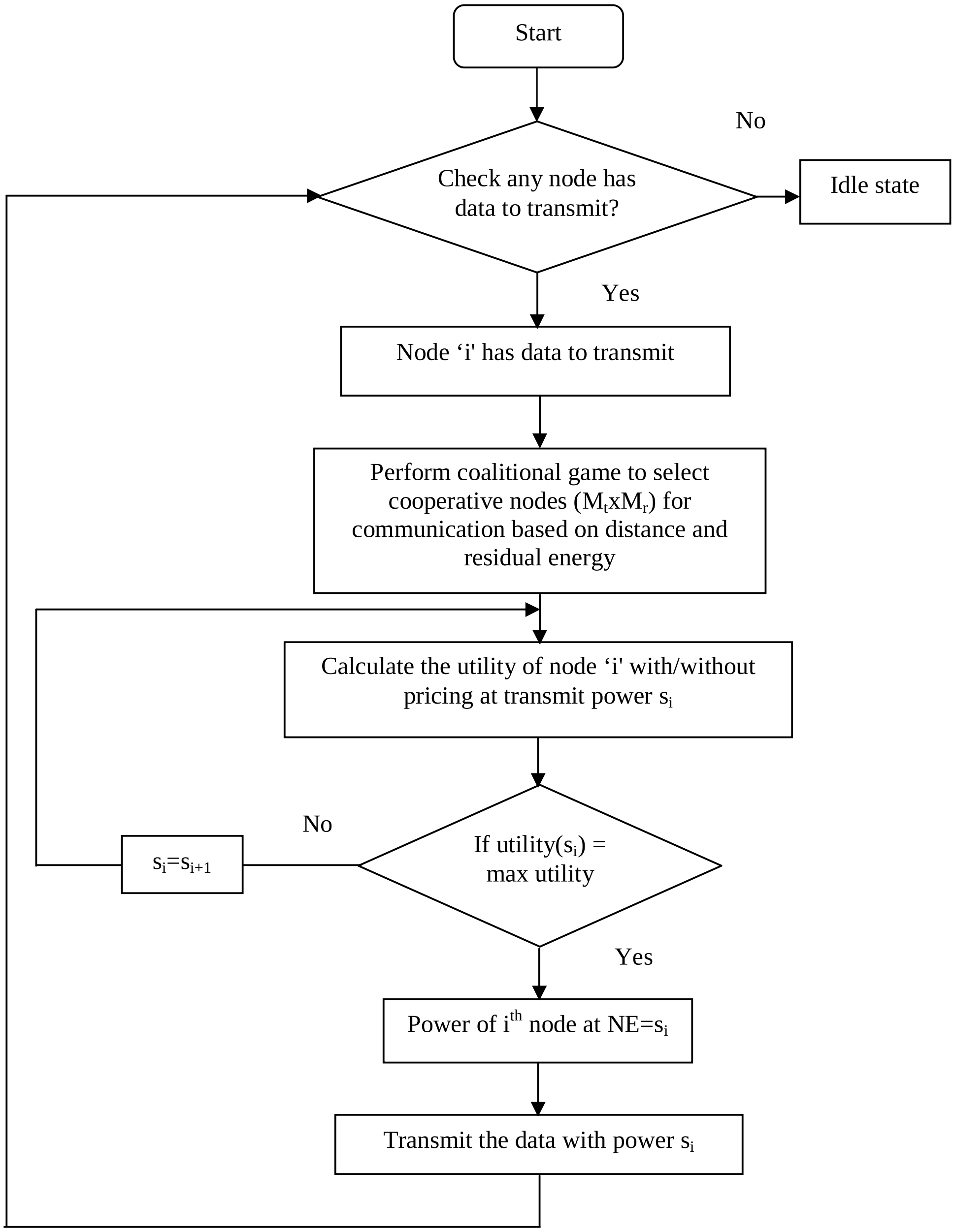


Fig.5.3. Flowchart of the power control game using VMIMO

5.6 RESULTS AND DISCUSSION

The analysis of the power control game using VMIMO is carried out using MATLAB 7.0. The number of transmit and receive antennas used are 2, 3 and 4. The cooperative nodes (M_t, M_r) are 2x2, 3x3, 4x4. The performance of cooperative MIMO with STBC using coalition game is evaluated in terms of utility, energy consumption incurred in the transmission of data packets from source to the destination node and network lifetime. The simulation parameters used for the analysis of VMIMO WSN is listed in Table 5.1.

Table 5.1 Simulation parameters for VMIMO WSN

Parameter	**Value**
Network area (A)	100×100m^2
Number of nodes (N)	100
Noise spectral density (σ^2)	-171dBm/Hz
Channel bandwidth (W)	1MHz
Data Rate (R)	20 kbps
Transmit power (s_i-s_{max})	(1-100)mW
Path loss component (h)	2
Initial energy of the node (E_i)	5J
Modulation technique	QPSK

5.6.1 Utility for VMIMO WSN

The utility without pricing for various diversity orders (2×2, 3×3 and 4×4) is shown in Fig.5.4. It can be discerned from this figure that utility for 4×4 antenna configuration is 4.97×10^8 bits/joule at the transmission power of 0.016W whereas 3×3 and 2×2 MIMO configurations provides the utility of 3.534×10^8 bits/joule and 1.985×10^8 bits/joule at the transmission powers of 0.0217W and 0.0338W respectively. The increase in utility is achieved due to the reduction of BER because of MIMO configurations.

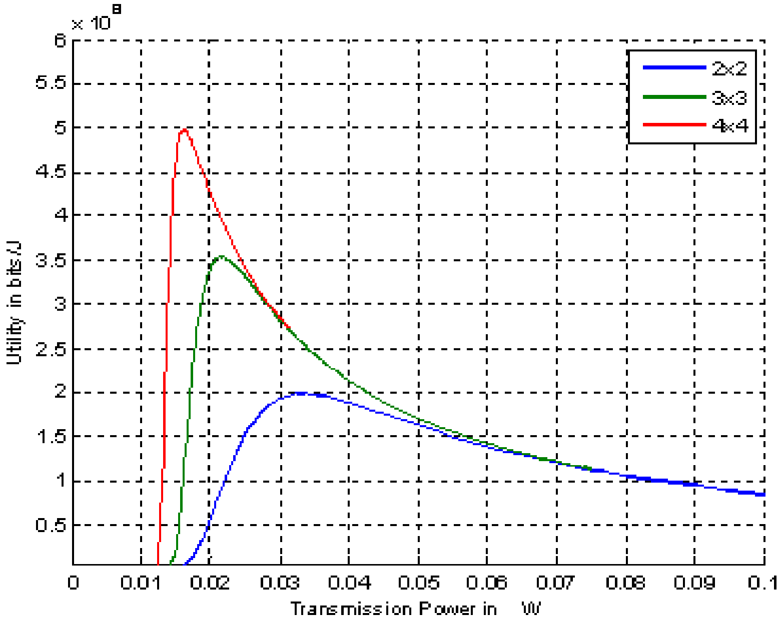


Fig.5.4. Utility without pricing for VMIMO WSN

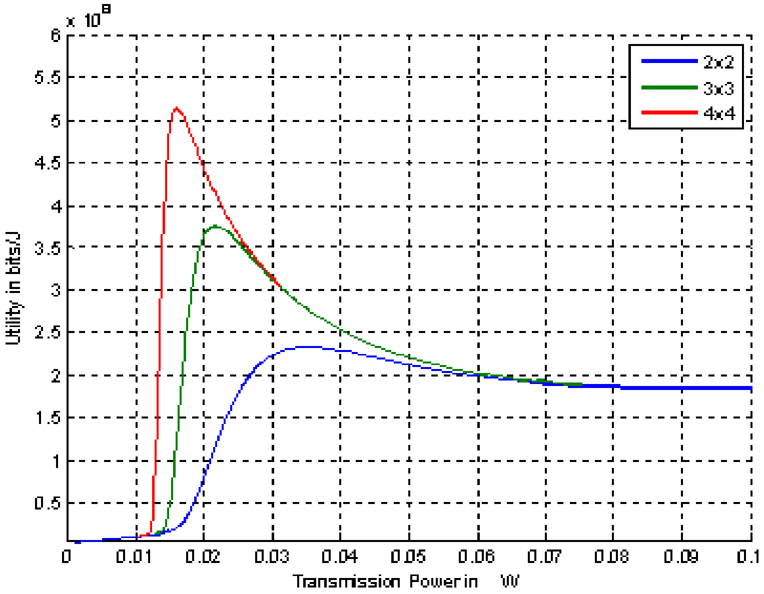


Fig.5.5. Utility with pricing for VMIMO WSN

Fig.5.5 demonstrates the utility with pricing of 4×4, 3×3 and 2×2 MIMO system using STBC schemes. It is evident from this figure that the utility with pricing is greater than the utility without pricing. An increase in utility by 4% is obtained by introducing the concept of pricing. This is due to the cooperation induced by the concept of pricing.

5.6.2 Power Efficiency of VMIMO WSN

Fig.5.6 shows the power efficiency attained in the case of cooperative MIMO scheme for varying SINR and transmitting power.

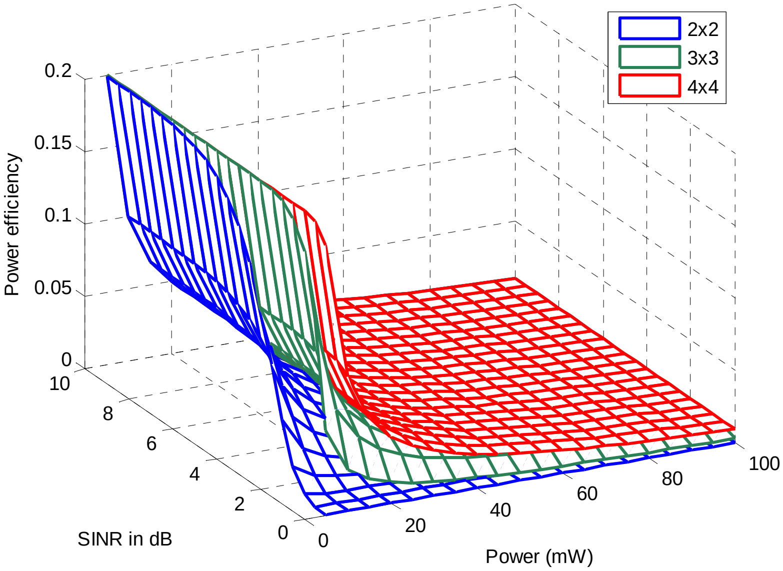


Fig.5.6. Power efficiency for VMIMO WSN

It is discerned the power efficiency decreases below the maximum if the transmit power is increased at high SINR. At low SINR power efficiency is very low for all power levels. 3x3 and 4x4 MIMO scheme provide a significant improvement in power efficiency compared to 2x2 MIMO. Considering a SINR of 5dB 4x4 MIMO scheme provides 11% and 6% increase in power efficiency compared to 2x2and 3x3 MIMO scheme respectively. This is due to the multiple antennas used during transmission and reception.

5.6.3 Energy Consumption Analysis of VMIMO WSN

The energy consumption of various diversity orders (2x2, 3x3 and 4x4) for STBC based cooperative MIMO scheme using coalitional game is presented in Fig.5.7.

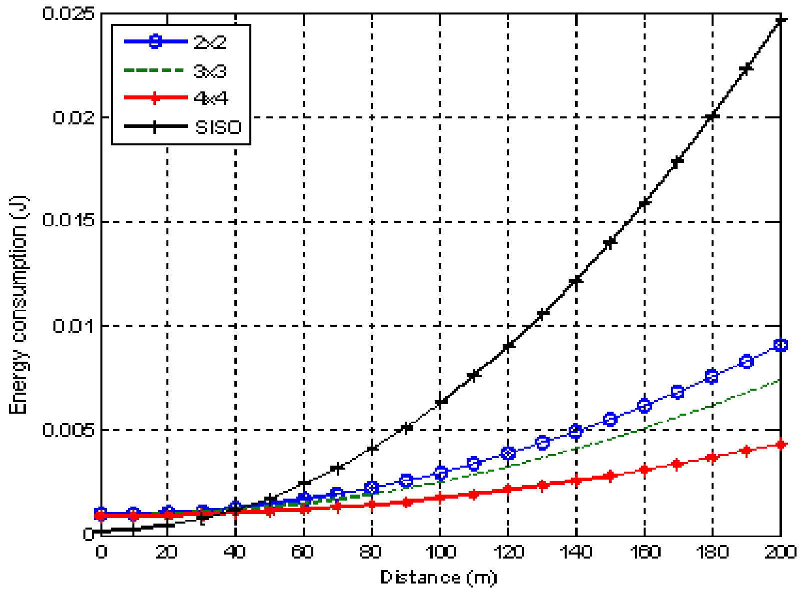


Fig.5.7. Energy consumption analysis for various diversity orders for VMIMO WSN

From this figure it is evident that as the distance between the transmitter and receiver increases, the energy consumption of the node gradually increases. STBC based 2x2 MIMO considerably reduces the energy consumption by 54% compared to SISO system, whereas 3x3 MIMO reduces the energy consumption by 16% compared to 2x2 MIMO scheme. Incorporating 4x4 MIMO further reduces the energy consumption by 20% compared to 3x3 MIMO scheme for a distance of 100m. The decrease in energy consumption is due to the increase in diversity order. However, 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 providing a little reduction in energy consumption.

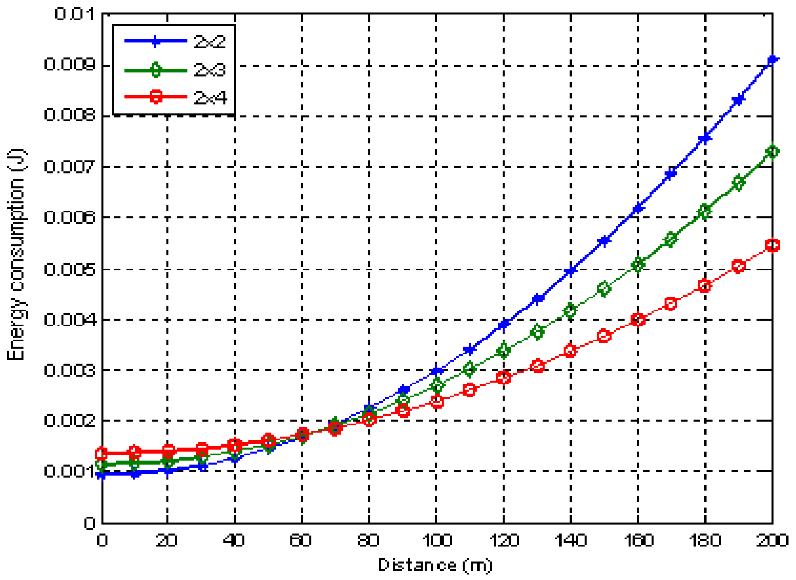


Fig.5.8. Energy consumption analysis considering receive diversity for 2 transmit antennas

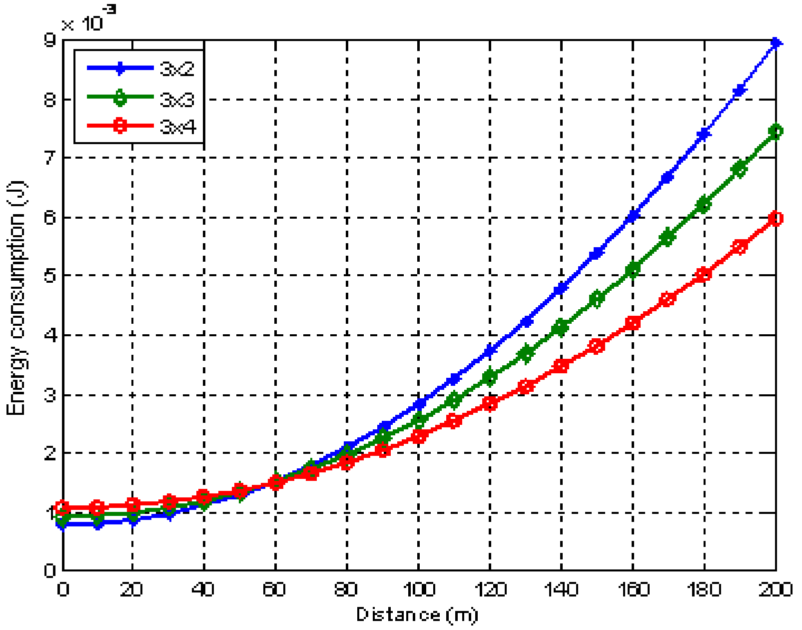


Fig.5.9. Energy consumption analysis considering receive diversity for 3 transmit antennas

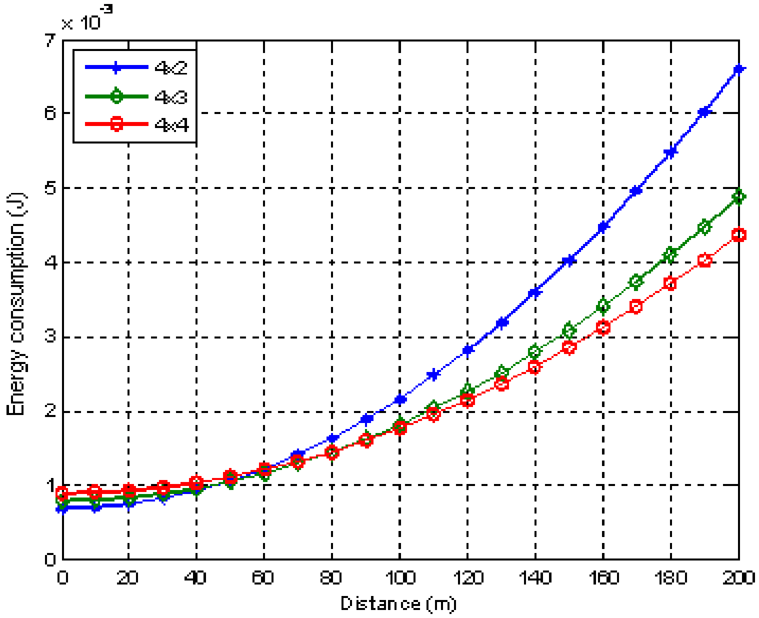


Fig.5.10. Energy consumption analysis considering receive diversity for 4 transmit antennas

The energy consumption considering receive diversity for 2, 3 and 4 transmit antennas are presented in Figs.5.8, 5.9 and 5.10 respectively. Higher order MIMO scheme requires lesser transmission power, however with increasing antennas the circuit power increases. Furthermore the variation in the communication distance leads to different proportion between transmission and circuit energies. Specifically, with increase in distance the transmission energy increases while the circuit energy remains approximately the same. For smaller distances, circuit power dominates, and hence lower diversity order is more energy-efficient than higher orders, whereas for longer distances, transmission power dominates and higher order MIMO schemes are energy efficient.

5.6.4 Network Lifetime Analysis of VMIMO WSN

Fig.5.11 shows the network lifetime of VMIMO WSN with the variation in distance. As the diversity order increases, the energy consumption decreases and the network lifetime increases.

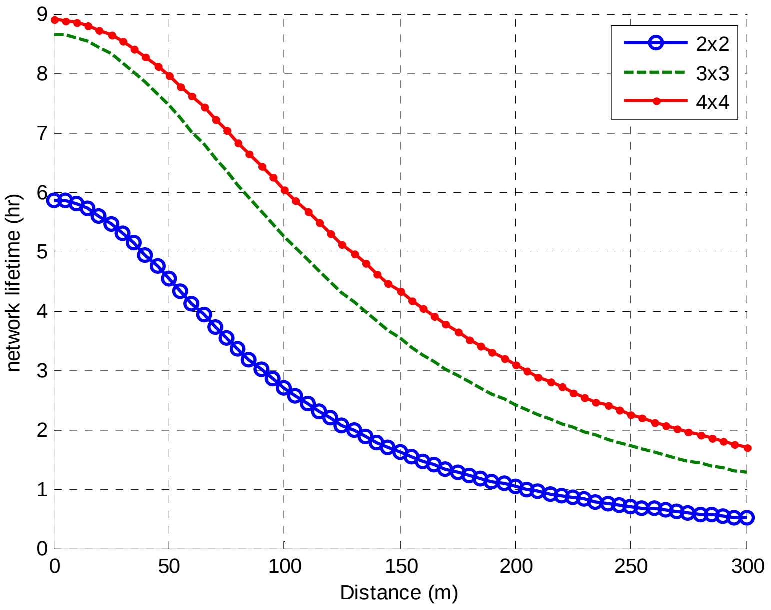


Fig.5.11. Network lifetime for VMIMO WSN

For a distance of 100m, it is inferred from Fig.5.11 that incorporating 3x3 MIMO increases the network lifetime by 93% compared to 2x2 MIMO scheme. 4x4 MIMO increases the network lifetime by 15% compared to 3x3 MIMO scheme.

5.7 POWER CONTROL WITH MIDRS CODES IN HEXAGONALLY DEPLOYED VMIMO WSN

ECC schemes can improve the system performance and has an impact on energy consumption. In particular, the error-correcting capability t_{MIDRS} of the MID algorithm of MIDRS code is greater for all rates which thereby maximises the energy efficiency of WSN. Further, hexagonal topology requires less number of active nodes, which inturn reduces the number of interfering nodes in WSN. Moreover, the communication in WSN occurs in tough environment which enables MIMO to be suitable for robust communication, by sending redundant information over the multiple antennas. The advantages of MIDRS, along with hexagonal deployment and MIMO schemes can be considered to provide power control solution for WSN in multipath fading environment. This section provides a power control solution considering MIDRS code in hexagonally deployed VMIMO WSN using game theoretic approach.

5.7.1 Utility Formulation for Hexagonal Deployment using MIDRS Codes in VMIMO WSN

The utility function of the ith transmitting node for hexagonal deployment using MIDRS codes in VMIMO WSN is obtained as

$$u_i^{v_j}\left(s_i,s_{-i}\right)_{MIDRS}=\sum_{k=1}^{M_r}\frac{LR_k}{F\sum_{i=1}^{\min(M_t,M_r)}\frac{s_i}{\min\left(M_t,M_r\right)}}\left(f\left(\gamma_k\right)_{MIDRS}\right) \tag{5.18}$$

BER for MIDRS code is derived as

$$BER_{MIDRS}\leq\frac{2^{m-1}}{n_{MIDRS}}\sum_{j=t_{MIDRS}+1}^{n_{MIDRS}}\frac{j+t_{MIDRS}}{n_{MIDRS}}\binom{n_{MIDRS}}{j}p_c{}^{j}(1-p_c)^{n_{MIDRS}-j} \tag{5.19}$$

Substituting the efficiency function given in eqn. (3.11) in eqn.(5.18), the utility function of the ith node becomes

$$u_i^{v_j}\left(s_i,s_{-i}\right)_{MIDRS}=\sum_{k=1}^{M_r}\frac{LR_k}{F\sum_{i=1}^{\min(M_t,M_r)}\frac{s_i}{\min\left(M_t,M_r\right)}}\left((1-2BER_{MIDRS})^F\right) \tag{5.20}$$

Substituting eqn.(5.19) in eqn.(5.20), the utility function of the ith nodes is given as

$$u_i^{v_j}\left(s_i,s_{-i}\right)_{MIDRS}=\sum_{k=1}^{M_r}\frac{LR_k}{F\sum_{i=1}^{\min(M_t,M_r)}\frac{s_i}{\min\left(M_t,M_r\right)}}\left(\left(1-2\left(\frac{2^{m-1}}{n_{MIDRS}}\sum_{j=t_{MIDRS}+1}^{n_{MIDRS}}\frac{j+t_{MIDRS}}{n_{MIDRS}}\binom{n_{MIDRS}}{j}p_c{}^{j}(1-p_c)^{n_{MIDRS}-j}\right)\right)^F\right) \tag{5.21}$$

5.7.2 Pricing Formulation for Hexagonal Deployment using MIDRS Codes in VMIMO WSN

The utility of the ith node with the pricing function included for hexagonal deployment using MIDRS codes in VMIMO WSN is obtained as

$$u_i^{v_j}(\text{pricing})_{\text{MIDRS}} = u_i^{v_j}(s_i, s_{-i})_{\text{MIDRS}} - A^{v_j}(s_i) \tag{5.22}$$

Substituting eqn.(5.20) in eqn.(5.22), the utility of the ith node is obtained as

$$u_i^{v_j}(\text{pricing})_{\text{MIDRS}} = \sum_{k=1}^{M_r} \frac{LR_k}{F \sum_{i=1}^{\min(M_t, M_r)} \frac{s_i}{\min(M_t, M_r)}} \left((1-2BER_{\text{MIDRS}})^F\right) - A^{v_j}(s_i) \tag{5.23}$$

On substituting eqn.(5.19) in eqn.(5.23), the utility function of the ith node is given as

$$u_i^{v_j}(\text{pricing})_{\text{MIDRS}} = \sum_{k=1}^{M_r} \frac{LR_k}{F \sum_{i=1}^{\min(M_t, M_r)} \frac{s_i}{\min(M_t, M_r)}} \left(\left(1-2\left(\frac{2^{m-1}}{n_{\text{MIDRS}}} \sum_{j=t_{\text{MIDRS}}+1}^{n_{\text{MIDRS}}} \frac{j+t_{\text{MIDRS}}}{n_{\text{MIDRS}}} \binom{n_{\text{MIDRS}}}{j} p_c{}^j (1-p_c)^{n_{\text{MIDRS}}-j}\right)\right)^F\right) - A^{v_j}(s_i) \tag{5.24}$$

The power efficiency considering MIDRS code in VMIMO WSN is given as

$$\eta_{\text{MIDRS\_VMIMO}} = \frac{(1-BER_{\text{MIDRS}})^F}{\frac{s_i}{\min(M_t, M_r)}} \tag{5.25}$$

5.8 RESULTS AND DISCUSSION

The analysis of the power control game using MIDRS code in hexagonally deployed VMIMO WSN is carried out using MATLAB 7.0. The performance is evaluated in terms of utility, energy consumption for transmission of data packets from source to the destination node and network lifetime.

Table 5.2 Simulation parameters for hexagonal deployment using MIDRS codes in VMIMO WSN

Parameter	**Value**
Network area (A)	100×100m^2
Maximum energy of a node	5J
Length of the code word in MIDRS code (n_{MIDRS})	62 bytes
Number of information symbols in MIDRS code (k_{MIDRS})	58 bytes
Modulation technique	QPSK
Number of encoders in MIDRS (M_n)	2
Number of transmit and receive antennas	2x2, 3x3, 4x4

5.8.1 Utility for Hexagonal Deployment using MIDRS Codes in VMIMO WSN

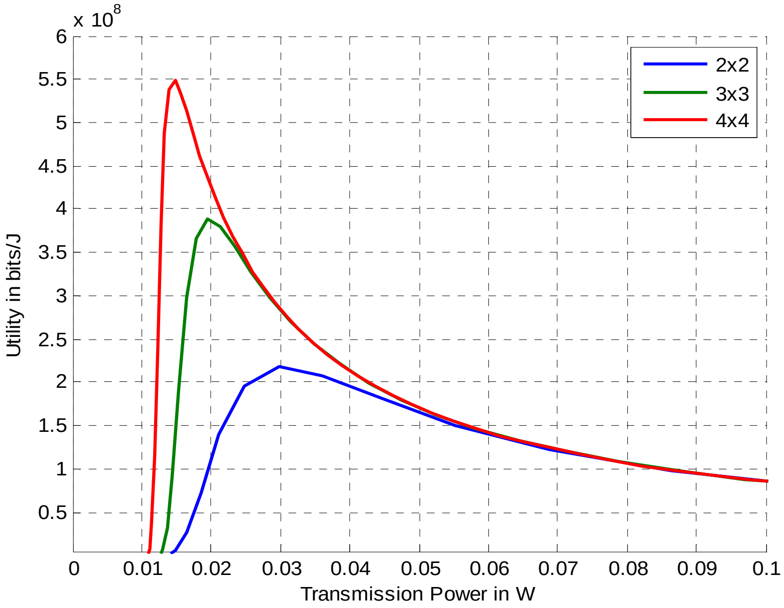


Fig.5.12. Utility of the game without pricing for Hexagonal Deployment using MIDRS codes in VMIMO WSN

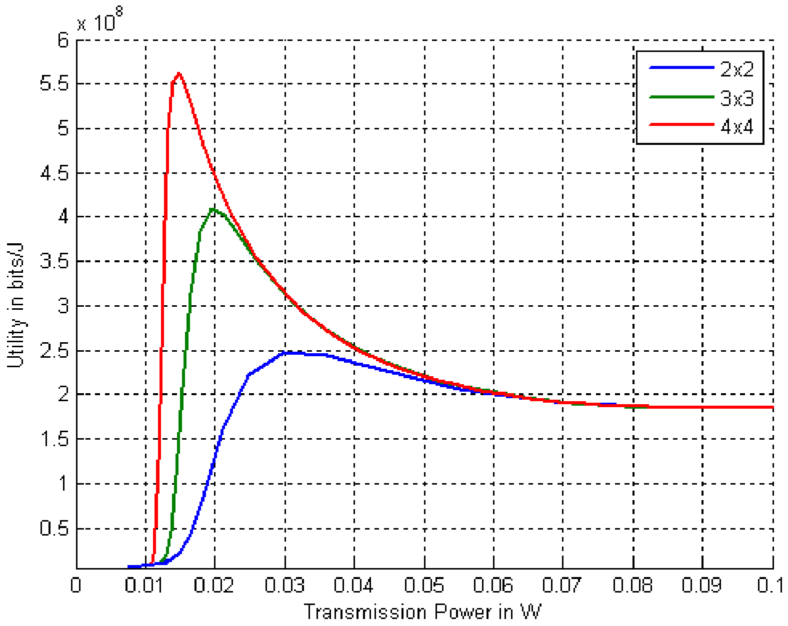


Fig.5.13. Utility of the game with pricing for Hexagonal Deployment using MIDRS codes in VMIMO WSN

Figs.5.12 and 5.13 elucidate the utility as a function of transmission power. Simulation results prove that 4x4 MIMO scheme with MIDRS code provides nearly 42% increase in utility for 26% reduction in power as compared to 3x3 MIMO scheme with MIDRS coding. Considering 4x4 MIMO scheme, the game without pricing provide an utility of 5.5x10^8 bits/joule for a transmission power of 14mW; whereas the game with pricing provides an utility of 5.6x10^8 bits/joule for the same transmission power, thereby offering 18% increase in utility.

5.8.2 Power Efficiency for Hexagonal Deployment using MIDRS Codes in VMIMO WSN

Fig.5.14 showcases the power efficiency attained in the case of VMIMO scheme using MIDRS codes for varying SINR and transmitting power. It is assayed that the power efficiency decreases below the maximum if the transmit power is increased at high SINR. 3x3 and 4x4 MIMO scheme provide an improvement in power efficiency compared to 2x2 MIMO. This is due to the multiple antennas used during transmission and reception.

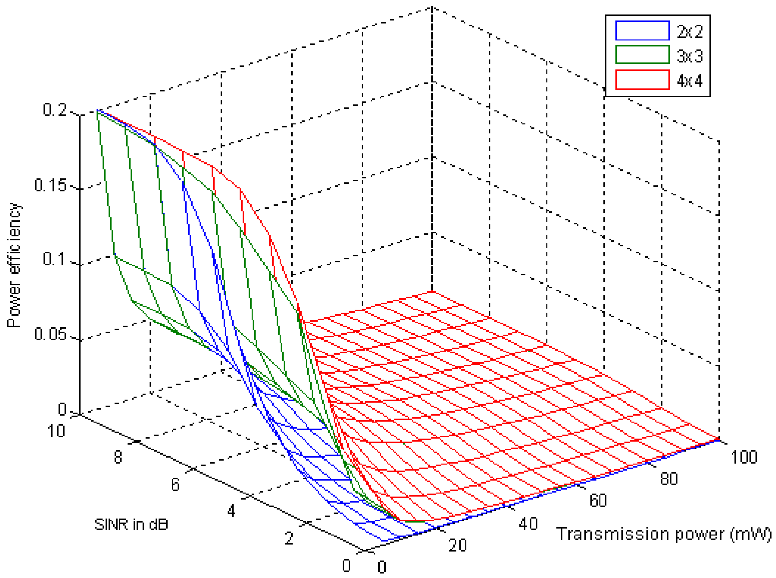


Fig.5.14. Power efficiency of the game with pricing for Hexagonal Deployment using MIDRS codes in VMIMO WSN

5.8.3 Energy Consumption for Hexagonal Deployment using MIDRS Codes in VMIMO WSN

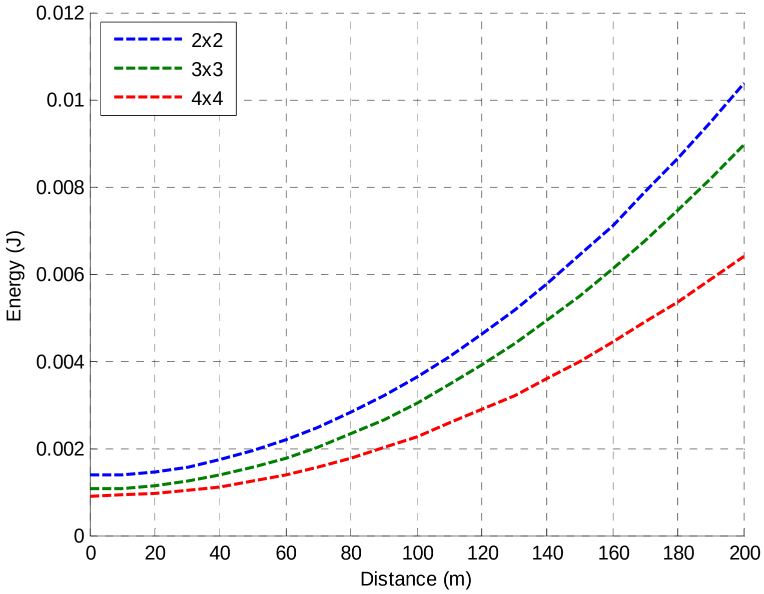


Fig.5.15. Energy consumption for various diversity orders for Hexagonal Deployment using MIDRS codes in VMIMO WSN

The energy consumption of various diversity orders (2x2, 3x3 and 4x4) for STBC based hexagonally VMIMO scheme using MIDRS code is presented in Fig.5.15. From this figure it is manifested that as the distance between the transmitter and receiver increases, the energy consumption of the node gradually increases. 3x3 MIMO with MIDRS coding reduces the energy consumption by 21% compared to 2x2 MIMO scheme. Incorporating 4x4 MIMO further reduces the energy consumption by 26% compared to 3x3 MIMO scheme for a distance of 100m.

5.8.4 Network Lifetime for Hexagonal Deployment using MIDRS Codes in VMIMO WSN

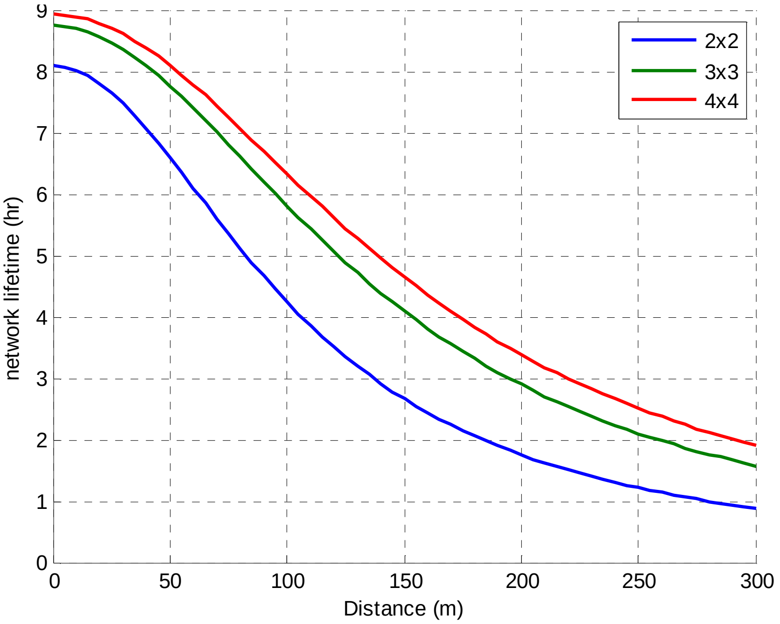


Fig.5.16. Network lifetime for Hexagonal Deployment using MIDRS codes in VMIMO WSN

Fig.5.16 shows the network lifetime with the variation in distance. For a distance of 100m, it is inferred from this figure that incorporating 4x4 MIMO increases the network lifetime by 14 % compared to 3x3 MIMO scheme.

5.9 SUMMARY

A coalitional game utilising cooperative transmission in wireless sensor network has been explored to maximise the network lifetime. The performance of the cooperative MIMO system is evaluated for various orders of diversity with STBC technique in terms of energy and network lifetime. Simulation results prove that 4x4 MIMO configuration performs better than its counterparts in terms of utility. Increase in utility by 4% is achieved by incorporating pricing mechanism in the power control game. The network lifetime is enhanced by 15% for a 4x4 MIMO scheme compared to 3x3 MIMO scheme. With increase in the diversity order the energy consumed is reduced significantly and the network lifetime is enhanced. This results from the reduction in BER and diversity gain of higher order MIMO configurations.

Hexagonally deployed VMIMO utilising STBC along with MIDRS code enables to achieve higher energy savings and longer network lifetime by allowing nodes to transmit and receive information jointly. Simulation results prove that 4x4 MIMO scheme with MIDRS code provides nearly 42% increase in utility for 26% reduction in power as compared to 3x3 MIMO scheme with MIDRS coding. With the inclusion of MIDRS code in VMIMO WSN the energy consumed is reduced significantly and the network lifetime is enhanced. 4x4 MIMO consumes 26% less energy consumption for packet transmission than 3x3 MIMO configuration. The network lifetime is enhanced by 14% for a 4x4 MIMO scheme compared to 3x3 MIMO scheme.

CHAPTER 6

POWER CONTROL GAME USING AMC

6.1 INTRODUCTION

In a WSN, each node transmits its information over the air and is prone to fading and other impairments. The data transmitted from the sensor nodes is highly susceptible to error in a wireless environment which leads to higher packet loss and thereby increases the transmit power. Error control coding is used to improve the system performance and is shown that ECC saves energy as compared to uncoded data transmission. Further to mitigate the fading effects in wireless channel, diversity techniques can also be used. Multi-Input Multi-Output scheme technology has the potential to enhance channel capacity and reduce transmission energy consumption particularly in fading channels. Another way to combat fading is the use of adaptive modulation which allows a wireless system to choose the highest order modulation depending on the channel conditions while ensuring that no harmful interference is caused to other nodes [138]. Since the non-adaptive methods require a fixed margin to maintain acceptable performance when the channel quality is poor, adaptive approaches result in better efficiency by taking advantage of the favourable channel conditions. After the physical layer sets the optimal modulation level, it will adjust the transmission power to stabilize at the optimal transmission power by the feedback based power control scheme. The adaptation of modulation and coding for controlling the transmission power is considered in this chapter.

6.2 ADAPTIVE MODULATION AND CODING

Spectrally efficient communication techniques are of great importance in wireless communications. To improve the spectral efficiency particularly over wireless fading channels, adaptive modulation or link adaptation is used. Adaptive modulation offers parameters such as data rate, transmit power, instantaneous BER, symbol rate, and channel code rate to be adjusted relative to the channel fading, by exploiting the channel information that is present at the transmitter.

A simple block diagram, of an adaptive modulation scheme, is shown in Fig.6.1.

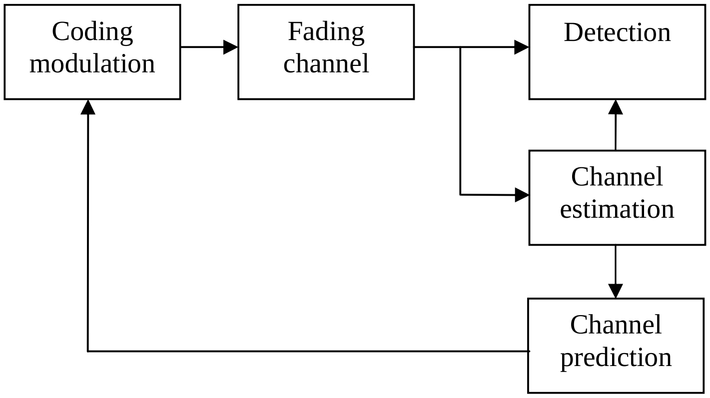


Fig. 6.1. Block diagram of adaptive modulation scheme

Adaptive modulation systems invariably require some Channel State Information (CSI) at the transmitter. This could be acquired by estimating and predicting the channel conditions at the receiver and fed back to the transmitter, so that the transmission scheme can be adapted relative to the channel characteristics.

During each transmission, the modulation scheme is adjusted to maximize the spectral efficiency, under BER and average power constraints, based on the instantaneous predicted SINR. The various modulation techniques such as QPSK and M-ary Quadrature Amplitude Modulation (M-QAM) schemes with different constellation sizes are provided at the transmitter. The link adaptation can employ QPSK for noisy channels, which are more robust and can tolerate higher levels of interference but has lower transmission bit rate. M-QAM is adapted for clearer channels, and has twice higher bit rate but is more prone to errors due to interference and noise. Hence it requires stronger FEC coding which in turn means more redundant bits and lower information bit rate.

To improve the quality of the wireless link the transmitter uses some form of channel coding. The coding can either be in the traditional form of coding followed by modulation (each done independent of the other) or joint coding and modulation [138]. Coding (more specifically, FEC) adds redundant bits to the data bits which can correct errors in the received bits. The degree of coding is determined by its rate, which is the proportion of data bits to coded bits. This typically varies from 1/8 to 4/5. In short when the channel changes the CSI is estimated at the transmitter and the transmitter decides the modulation and coding parameters to be used.

6.3 GAME THEORETIC MODELLING FOR AMC

In a non-cooperative game for power control using AMC, each node adjusts its modulation type and power to maximize its corresponding utility. The game is defined as a triple $G =[N,\{S_i, M_i\},U_i]$

where

$N = \{1, 2, 3 \ldots x\}$ is the set of players,

$\{S_i, M_i\}$ is the set of actions, available for the player 'i' to make a decision.

$U_i= \{u_1, u_2, .., u_i\}$ is the payoff that results from the strategy profile.

Each node selects modulation and coding $m_i \in M_i$ and the corresponding power level $s_i \in S_i$ from the set of actions. The various modulation types considered are QPSK, 16QAM, 32QAM, 64QAM with code rates 1/8, 1/5, 1/4, 1/3, 1/2, 2/3, 4/5. The power levels available vary from minimum transmission power level s_{min} to maximum transmission power level s_{max} and are chosen to be continuous.

Since the game is an iterative process, the players are allowed to select the strategy (power level, modulation type with coding) that maximizes their utility function for each iterative process. At the receiving end channel SINR is estimated and predicted and then fedback to the transmitter to select the suitable Modulation and Coding Scheme (MCS) from the strategy set to maximize utility at that SINR.

6.3.1 Utility Formulation for AMC

Consider node 'i' is transmitting data to the sink node. The SINR of the ith node (γ_i) considering the residual energy is given as,

$$\gamma_i = (PG)\frac{h_i s_i \frac{E_m}{E_{ir}}}{\sum_{k=1,k\neq i}^{N} h_k s_k \frac{E_m}{E_{kr}} + \sigma^2} \tag{6.1}$$

The prime objective of each node is to maximize its utility without consuming much power. The utility function for AMC is given as

$$u_i(s_i, \gamma_i) = \eta_{eff,MCH} = M_{sym} R_{coding} f(\gamma_i) \tag{6.2}$$

where

M_{sym} is the number of bits of each symbol that can be modulated by the type of MCS selected

R_{coding} is the coding efficiency

The efficiency function $f(\gamma_i)$ is given as

$$f(\gamma_i) = (1 - 2P_e)^{F \times M_{sym}} \tag{6.3}$$

The AMC selects appropriate MCS according to the change of SINR in order to maximize the effective modulation and efficiency. The nodes iteratively decide its transmission power level by maximizing its utility function. The ideal AMC is given by

$$\eta_{eff,AMC} = \max\left(\eta_{eff,MC1}, \eta_{eff,MC2} \ldots\ldots \eta_{eff,MCn}\right) \tag{6.4}$$

From the non cooperative nature of the game it is inferred that, an attempt to maximize the utility of a node consumes maximum power. This creates excessive interference, leading to performance degradation. As a solution to this problem, pricing is introduced and this induces a degree of cooperation among players, brings an improvement in system performance by penalizing the selfish players (nodes) and enables the nodes to communicate with a relatively low and stable transmission power.

The pricing function is given by,

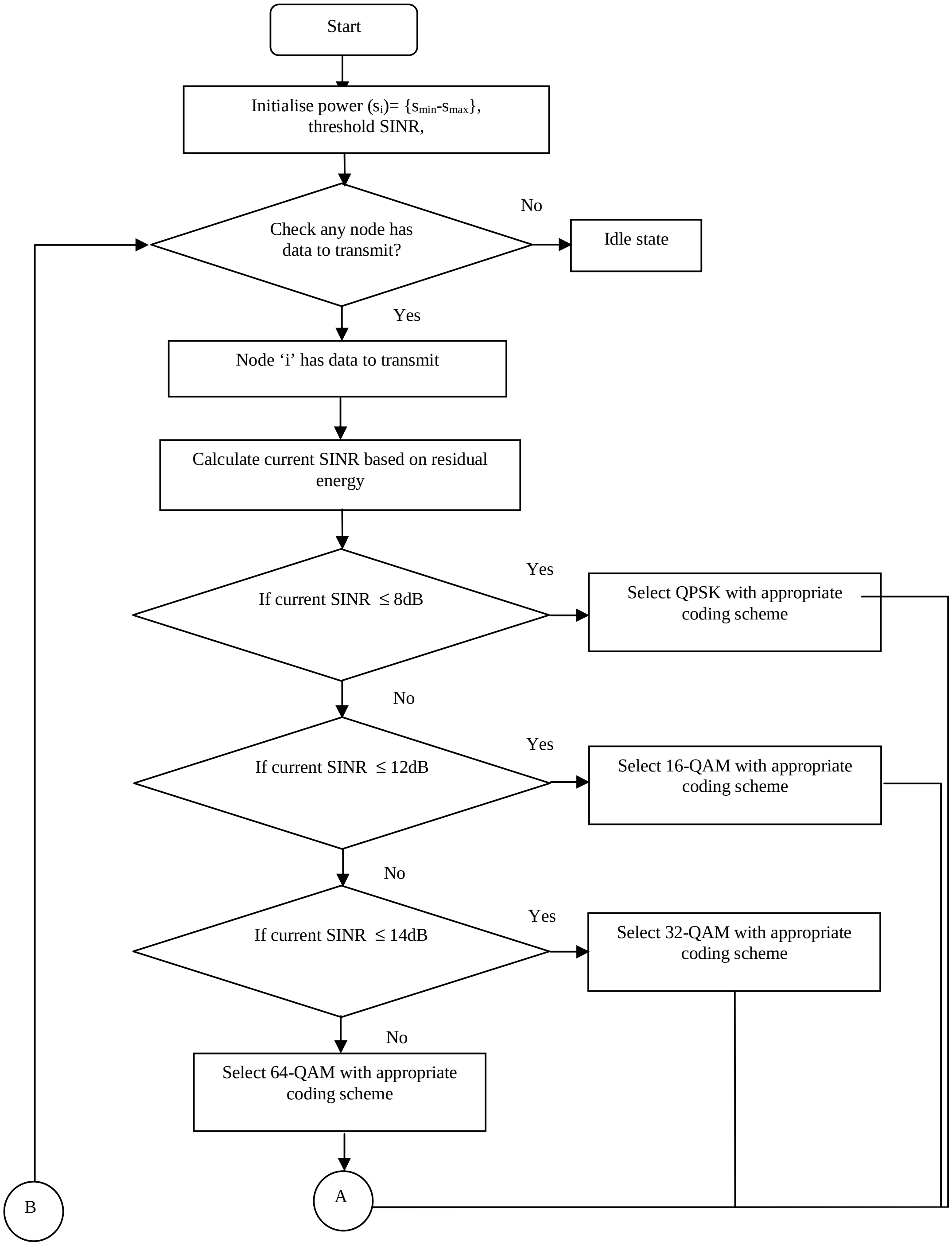
$$A\left(s_i\right) = chs_i \frac{E_m}{E_i} \tag{6.5}$$

The utility function with pricing considering AMC is given by

$$u_i^c\left(s_i, \gamma_i\right) = u_i\left(s_i, \gamma_i\right) - A\left(s_i\right) \tag{6.6}$$

The flowchart of the proposed game is given in Fig.6.2. The main objective of this game is that each transmitting node adjusts its modulation type and power level in order to maintain certain QoS under the constraint of target BER and SINR requirement. It is assumed that source node ‘i’ has data to transmit to the sink node. The first step in the game is to initialize the threshold SINR values for various modulation types. Based on the residual energy of the node, current SINR of the channel is calculated and compared with threshold SINR value. If the current SINR is less than or equal to 8dB, QPSK modulation with appropriate coding scheme that maximizes the utility is selected. On the other hand if the current SINR is greater than 8dB and less than or equal to 12dB, 16-QAM modulation with suitable coding scheme is adopted. 32-QAM with coding is selected if the SINR range falls within 12dB and 14dB. Otherwise if the current SINR is greater than 14dB, 64-QAM with proper coding scheme is chosen. Subsequently the node calculates the utility with/without pricing for the MCS selected. If this utility is not equal to the maximum utility, then the power is incremented and new utility is calculated. This step is repeated until to obtain maximum utility, where the NE point exists. The power at this point is the optimal power and is given by

$$s_i = \arg\max_{s_i \in S_i} \left\{u_i\left(s_i, \gamma_i\right)\right\} \tag{6.7}$$


Start
Initialise power (s_i)= {s_{min}-s_{max}}, threshold SINR,
Check any node has data to transmit?
No
Idle state
Yes
Node 'i' has data to transmit
Calculate current SINR based on residual energy
If current SINR ≤ 8dB
Yes
Select QPSK with appropriate coding scheme
No
If current SINR ≤ 12dB
Yes
Select 16-QAM with appropriate coding scheme
No
If current SINR ≤ 14dB
Yes
Select 32-QAM with appropriate coding scheme
No
Select 64-QAM with appropriate coding scheme
B
A

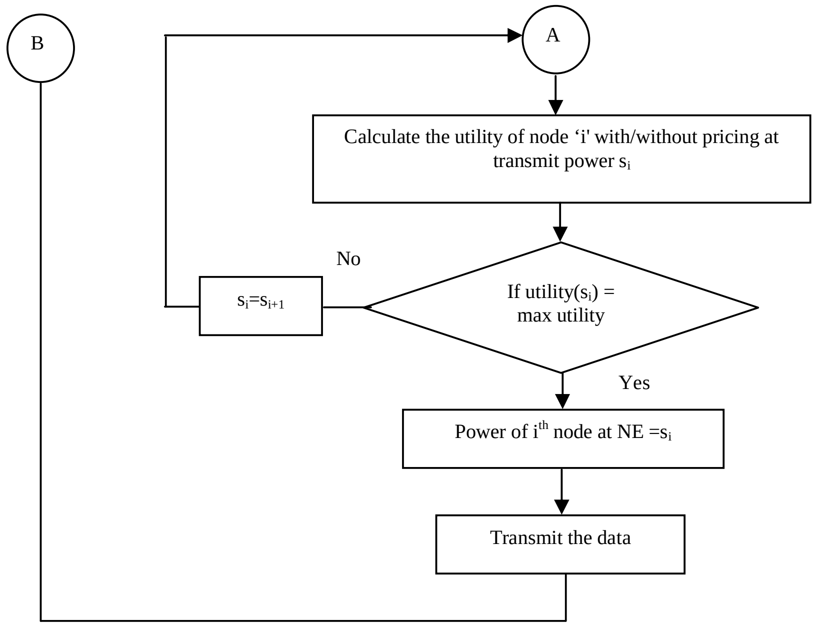


Fig. 6.2. Flowchart of the proposed power control game with AMC

6.4 RESULTS AND DISCUSSION

The performances of the power control game using AMC for wireless sensor network are evaluated using MATLAB 7.0 in terms of utility, power efficiency and energy consumption. The simulation parameters are listed in Table 6.1.

Table 6.1 Simulation parameters for AMC

Simulation parameters	**Description**
Network area	100×100m^2
Transmit power $\{s_{min}:s_{max}\}$	1-100mw
Channel Bandwidth	1MHz
Noise spectral density	-171dBm/Hz
Path loss component	2
Modulation techniques	QPSK, 16-QAM, 32-QAM, 64-QAM
Code rates	1/8, 1/5,1/4, 1/3, 1/2, 2/3, 4/5

6.4.1 Utility with AMC

The utility of the game with and without pricing considering residual energy check for various modulation techniques is obtained (Fig. 6.3).

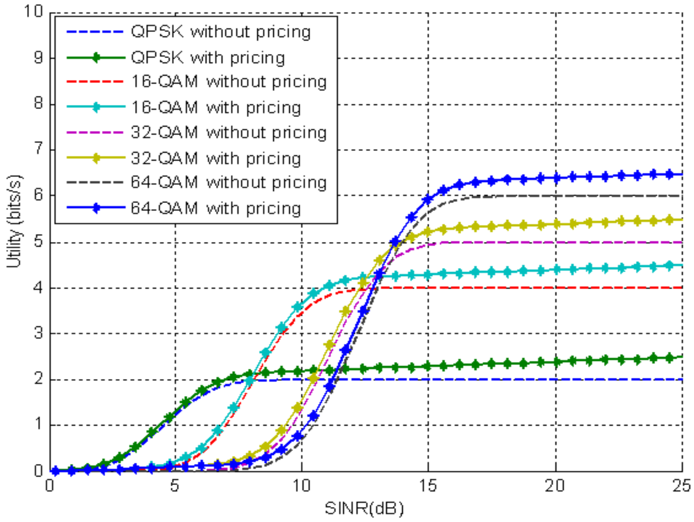


Fig. 6.3. Utility of the game with energy check

From this figure it is evident that for QPSK modulation without pricing, utility of 2 bps is obtained for SINR of 8dB, whereas with pricing 2.15 bps is achieved, thereby providing 7.5% increase in utility. As the channel condition improves higher order modulation schemes are selected. It can be further seen from this figure that the utility of the game without pricing considering residual energy check for various modulation techniques 16-QAM, 32-QAM and 64-QAM, for SINR of 11dB, 13dB and 16dB are 3.8 bps, 4.5 bps and 5.94 bps respectively. For the modulation techniques 16-QAM, 32-QAM and 64-QAM and for the same SINR under consideration, the game with pricing provides utility of 3.9 bps, 4.6 bps and 6.1 bps respectively.

Pricing scheme provides nearly 26% increase in utility compared to that without pricing. The improvement in utility is due to pricing which induces cooperation among players and brings an improvement in system performance by punishing the selfish nodes. This enables the nodes to communicate with a relatively low and stable transmission power. The utility of the game with and without pricing for the various modulation schemes adopted is tabulated in Table. 6.2

Table 6.2 Comparison of utility of the game with energy check

SINR(dB)	Modulation scheme selected	Utility without pricing (bps)	Utility with pricing (bps)
8	QPSK	2	2.15
11	16-QAM	3.8	3.9
13	32-QAM	4.5	4.6
16	64-QAM	5.94	6.1

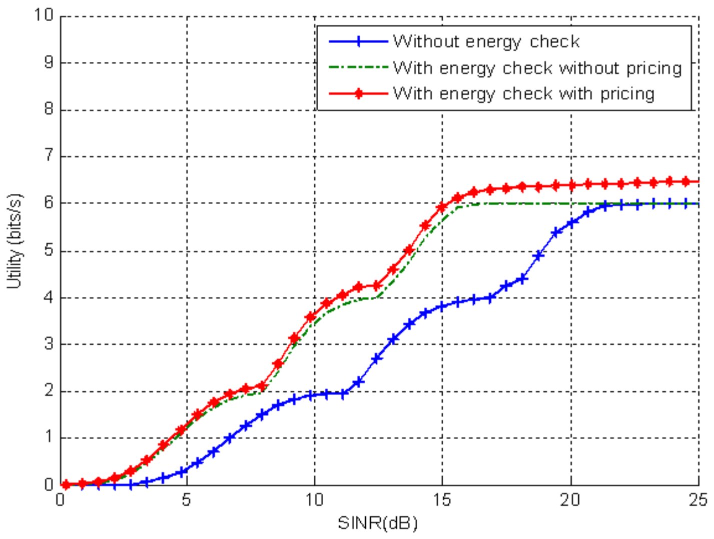


Fig.6.4. Utility of the game using AMC with and without energy check

Fig.6.4 shows the utility function of the game with AMC for varying SINR with and without residual energy check. From this figure it is evident that, on considering QPSK modulation, without residual energy check maximum utility is obtained for a SINR of 10dB, whereas with residual energy check it is attained at a SINR of 8dB thus providing 30% improvement in utility. Since SINR is directly related to transmission power, the increase in utility is due to the reduction in the number of interfering nodes in the network.

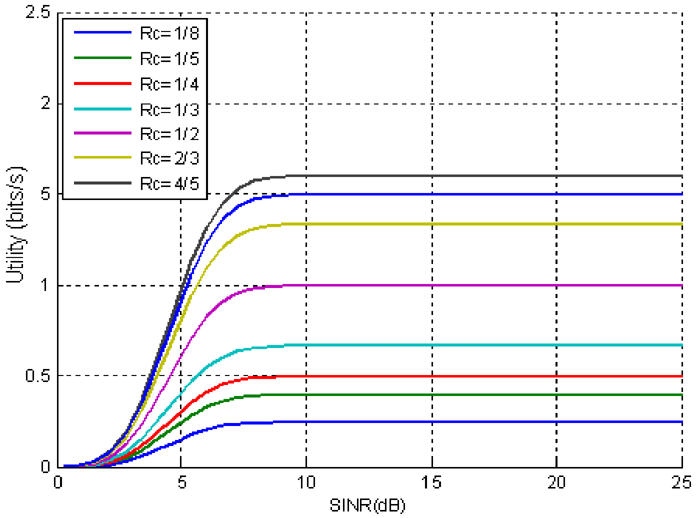


Fig.6.5. Utility of the game without pricing for QPSK modulation

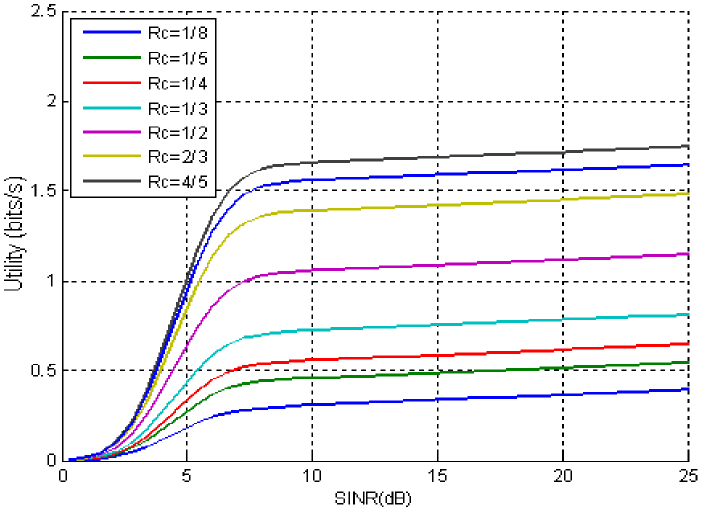


Fig.6.6. Utility of the game with pricing for QPSK modulation

The utility of the game with and without pricing considering residual energy check and QPSK modulation for various code rates are shown in Fig.6.5 and Fig.6.6 respectively. As the coding efficiency increases the utility increases. It is manifested from the figures that, the game without pricing provides an utility of 1.5 bps, whereas with pricing an utility of 1.8 bps is achieved, thereby providing 20% increase in utility for a SINR of 7dB and coding efficiency of 4/5.

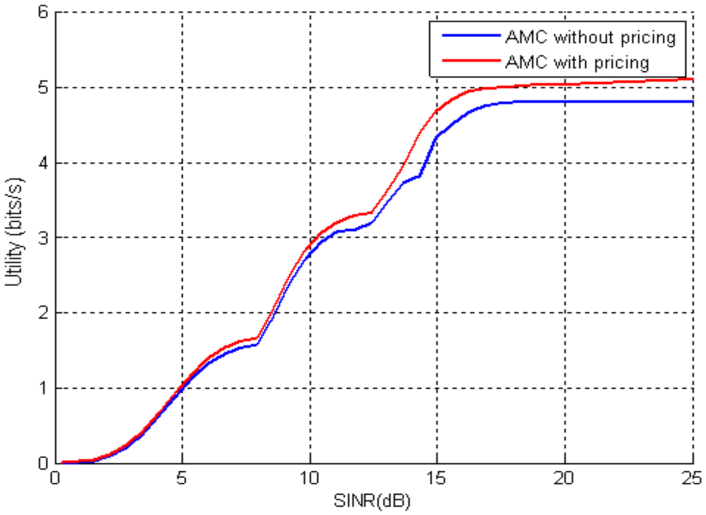


Fig.6.7. Utility of the game using AMC with and without energy check for coding efficiency of 4/5

Fig.6.7 shows the utility of the adaptive game with and without energy check for coding efficiency of 4/5. The figure depicts that with the change in channel condition various modulation schemes are adopted, so that higher utility is achieved. QPSK modulation is adopted during worse channel conditions. It is manifested from figure 6.4 that, the game without pricing provides an utility of 1.5 bps, whereas with pricing an utility of 1.6 bps is achieved, thereby providing 6% increase in utility for a SINR of 7dB and coding efficiency of 4/5. Higher order modulations with higher coding rates are adopted when the channel condition improves. If the current SINR is greater than 8dB and less than or eqaul to 12dB 16-QAM is adopted. It is obvious from the figure that at a SINR of 11dB, the game with pricing provides an increase in utility by 13% compared to that without pricing. At a SINR of 14dB, the game without pricing gives an utility of 3.7 bps. The game with pricing provides an increase in utility by 8% compared to that without pricing. Considering 64-QAM, it is apparent that at a SINR of 17dB and a coding efficiency of 4/5, game without pricing provides a utility of 4.5 bps. The game with pricing offers an incentive in utility by 13% compared to that without pricing.

6.4.2 Power Efficiency with AMC

Power efficiency considering the QPSK, 16-QAM, 32-QAM and 64-QAM schemes is shown in Fig.6.8.

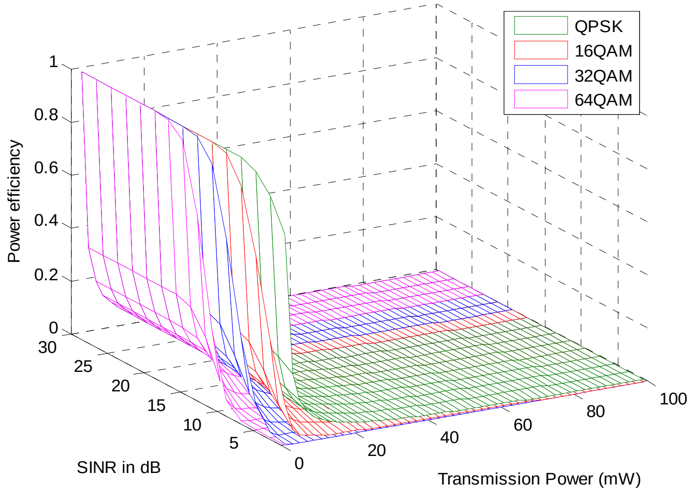


Fig.6.8. Power efficiency for various modulation techniques

Higher rate modulation schemes are adopted during periods of low fade. Periods of high fade lowers the effective SINR, and low rate modulation are adopted to make transmission more robust. It is inferred from the figure that at high SINR increasing the transmitting power unnecessarily decreases the power efficiency below the maximum. Hence at high SINR, a node should transmit at low power to maximise its power efficiency. At low SINR the power efficiency is very low for all power levels and hence the node should not transmit under such worse channel conditions. When the channel condition is poor, the system adopts QPSK modulation and shifts to higher order modulation with improvement in channel condition.

6.4.3 Energy Consumption with AMC

The energy consumption of the node in Joules for various modulation schemes with coding efficiency of 4/5 is determined. Table.6.3 demonstrates the energy consumption of the node at a distance of 50m for various modulation schemes with coding efficiency of 4/5

Table 6.3 Energy consumption at a distance of 50m for various modulation schemes and coding efficiency of 4/5

SINR(dB)	Energy Consumption(J)			
	QPSK	**16 QAM**	**32 QAM**	**64 QAM**
8	0.01395	0.01769	0.02144	0.02519
11	0.04985	0.03124	0.03683	0.04231
13	0.06479	0.06126	0.05121	0.05789
16	0.07805	0.07284	0.06764	0.06244

From this Table 6.3 it is evident that as the SINR increases the energy consumption of the node gradually increases. Under worst channel condition QPSK is more energy efficient by 21%, 35% and 44% compared to 16-QAM, 32-QAM and 64-QAM respectively. With the change in channel condition appropriate modulation scheme is adopted to provide energy efficient communication. For the SINR of 16dB, 64 QAM is adopted and the energy consumption is reduced by 7%, 14% and 20% compared to 32-QAM, 16-QAM and QPSK respectively.

6.5 SUMMARY

An energy efficient adaptive modulation and coding for power control and lifetime enhancement in WSN using game theoretic approach taking into account the residual energy of the nodes has been analysed. The game is designed such that, appropriate modulation and coding is selected based on the current channel condition. The utility of the nodes without residual energy check and with residual energy check are compared. The maximum utility is obtained when energy check is considered. With the inclusion of pricing the interference among the nodes due to the optimizing behaviour of a particular node is suppressed. Further the result shows that employing residual energy check with pricing achieves the best response for the sensor nodes.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 GENERAL

An attempt has been made in the present work to enhance the lifetime of WSN through game based power control approach by using ECC, appropriate node deployment scheme, MIMO technique and AMC. The summary, salient conclusions and scope for further research work are presented in this chapter.

7.2 SUMMARY

The advancements in wireless communication have dictated the need of WSN with infrastructure free support to intervene with hostile environment. The principal deliberation of WSN has been to save energy and to enhance the lifetime of the network.

In the present work, an attempt has been made to develop a game theoretic framework considering ECC to improve the sensor network lifetime. In addition, a proper node deployment scheme that minimizes the number of interfering nodes in the network has been analysed to minimize power consumption of the sensor node. 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 were used to reduce the retransmission probability so as to improve energy savings. Diversity techniques involving space time block code have been visualized in this work. The sensors are deployed in harsh environments and left unattended. To maximize the utility in such environment, adaptive modulation and coding schemes have been incorporated to devise the power control game.

7.3 CONCLUSIONS

Power Control Game using ECC

The performance of the proposed power control game using ECC was examined through simulation analysis and compared with the uncoded scheme.

- Uncoded scheme provided a maximum utility of only 4.346×10^5 bits/joule for a transmission power of 36mW. The RS and MIDRS coding schemes achieved the utility of 5.549×10^5 bits/joule and 6.4×10^5 bits/joule for a transmission power of 28mW and 24mW respectively. The increase in utility and decrease in transmission power of the game with MIDRS coding is due to the greater error-correction radius t_{MIDRS} of the MID algorithm.
- The utility of the power control game with pricing scheme was more than the power control game without pricing scheme. The pricing scheme has increased the utility by 6% by implicitly inducing cooperation and yet maintaining the non cooperative nature of the resulting power control solution.
- RS and MIDRS codes have improved power efficiency by 31% and 43% respectively over uncoded scheme for a particular SINR value of 7dB.
- The game with RS and MIDRS codes decreased the energy consumption by about 28.6% and 38.7% respectively for the spacing of 50m between the source and the sink.

Power Control Game with Deployment Schemes

A game theoretic model with pricing for power control taking into account the residual energy of the nodes in a sensor network considering various deployment schemes has been analysed.

- The maximum utility was obtained at minimal transmission power for hexagonal deployment scheme. It is due to the less number of active and interfering nodes in hexagonal deployment scheme.
- The game theory model with pricing considering residual energy check has significantly increased lifetime than without pricing and energy check scheme.
- The lifetime of hexagonally deployed WSN using residual energy check scheme with pricing was 55% and 66% higher for the distance of 20m and 35m respectively than without residual energy check scheme.
- Also, the residual energy check scheme with pricing achieved 14% and 40% higher network lifetime for 20m and 35m respectively than network without pricing.

Power Control Game using VMIMO

Further, virtual MIMO scheme utilising STBC was propounded to combat channel fading effects to ensure packet transmissions between sensor nodes. The performance of the VMIMO system was evaluated for various orders of diversity with STBC.

- Simulation results disclosed that 4x4 MIMO configuration with space time code, perform better than other diversity orders. The pricing mechanism incorporated in the power control game increased the utility by 4%.
- Further, the energy consumption has been significantly reduced with increase in the diversity order. The network lifetime was 15% higher in 4x4 MIMO scheme than in 3x3 MIMO scheme. The increase in lifetime of the network is due to the reduction in BER and diversity gain of higher order MIMO configurations.

- The 4x4 MIMO scheme with MIDRS code achieved about 42% higher utility with 26% reduction in power than 3x3 MIMO scheme with MIDRS coding.

- Further, 4x4 MIMO with MIDRS code consumed 26% less energy for packet transmission than 3x3 MIMO configuration.

- Also, the network lifetime for a 4x4 MIMO scheme with MIDRS code was 14% higher than 3x3 MIMO scheme.

Power Control Game with AMC

Finally, the game theory based energy efficient adaptive modulation and coding for power control has been analysed to enhance the lifetime of WSN by taking into account the residual energy of the nodes.

- An utility of 1.5bps and 1.6bps is achieved at a SINR of 7dB with QPSK modulation for the game without and with pricing respectively. The pricing scheme has provided 6% higher utility than without pricing scheme.

- The game with pricing provided 13% higher utility than without pricing at a SINR of 11dB with 16-QAM modulation.

- The game without pricing achieved an utility of 3.7 bps at a SINR of 14dB with 32-QAM,. The game with pricing provided 8% higher utility than without pricing.

- Further, the game without pricing provided an utility of 4.5bps at a SINR of 17dB with 64-QAM. The game with pricing offered an incentive of 13% utility than without pricing.

- The rise in SINR has increased the energy consumption of the node gradually. It has been observed that, QPSK is more energy efficient by

21%, 35% and 44% than 16-QAM, 32-QAM and 64-QAM respectively under worst channel condition. The energy consumption of a node at SINR of 16dB with 64-QAM was 7%, 14% and 20% less than 32-QAM, 16-QAM and QPSK respectively.

The outcome of the present work shows that the utility is enhanced and energy consumption is reduced significantly with the power control games using ECC, various deployment schemes, VMIMO and AMC. 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 areas that might be interesting for researchers to pursue and explore in future.

i. The algorithms can be plugged to real test-bed to study the performances.

ii. Efforts can be made to provide an energy efficient solution by using other power control techniques such as water filling algorithm in the game based approach.

iii. Node sleep/wake schemes for power control can be explored.

iv. The game theoretic approaches pertaining to the transport layer of sensor network for end to end communication can also be an area worth to be investigated.

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