Utility enhancement by power control in WSN with hexagonal deployment scheme using game theoretic approach with pricing

R.Valli and P.Dananjayan

Abstract— The fundamental component of resource management in Wireless Sensor Network (WSN) is transmitter power control since they are miniature battery powered devices. An efficient power control technique is essential to maintain reliable communication links in wireless sensor network (WSN) and to maintain the battery life of the sensor node and in turn the sensor network. This paper analyses a game theoretic model with pricing for power control taking into account the residual energy of the nodes in a homogeneous sensor network considering square grid, triangular and hexagonal deployment schemes. The utility with pricing that minimizes the power consumption of the nodes is analysed. Simulation results show that, for hexagonal deployment scheme, with the inclusion of residual energy check in the game, the transmitting power of the nodes is reduced thereby saving energy and increasing the network lifetime.

Keywords— Game theory, Pricing, Power control, Wireless sensor network

I. Introduction

Due to recent advances in wireless communication and micro electronics over the last few years, the development of networks of low cost, low power and multifunctional sensors have received increasing attention. A wireless sensor network (WSN) consists of hundreds or thousands of low cost nodes which could either have a fixed location or randomly deployed to monitor the environment [1, 2]. The deployed sensors register changes to physical stimuli and these sensor readings are processed by a tiny on-board computer, which wirelessly communicate the results to a central computer. WSNs are used to monitor ecosystems, wild and urban environments. They have been vital in predicting events that threaten species and environments, including gathering information from animal habitats, in volcanic activity monitoring, flash-flood alerts and environmental monitoring. Wireless sensing in densely populated urban communities can be invaluable not only in monitoring the physical environment, but also for focusing on the impact people and their vehicles have on that environment through mobile emissions monitoring [3].

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To cater all these needs WSN should operate as long as possible without replacement of the batteries. Therefore energy conservation is very crucial for WSNs, both for each sensor node and the entire network to prolong the network lifetime. Since radio communication is the major source of energy consumption in WSNs, topology control mechanisms are fundamental to achieving good network energy efficiency and for extending the network lifetime. Numerous challenges are faced while designing WSNs, maintaining connectivity and maximizing the network lifetime over critical considerations. The connectivity is met by deploying a sufficient number of sensors, or using nodes with long-range communication capabilities to maintain a connected graph. The network lifetime can be increased through energy conserving methods such as using energy efficient protocols, algorithms and topology control [4].

Topology control has been premeditated broadly in the recent years [5]. The intention is to manage the topology of the graph representing the communication links between network nodes with the purpose of maintaining connectivity, while reducing energy consumption and/or interference. Topology control has the beneficial effect of minimizing contention when accessing the wireless channel besides reducing energy consumption. In general, when the nodes transmitting ranges are relatively short, many nodes can transmit simultaneously without interfering with each other, and the network capacity is enhanced. In recent years, more light has been thrown on research on power control for WSNs, and a lot of power control mechanisms [6] have been projected which try to design simple and practical protocols that build and maintain a sensibly good topology. Most works on topology control are based on adjustable transmission power control and primarily spot on maintaining a connected topology while minimizing energy consumption of nodes to extend the lifetime of network [5]. In [7] Wattenhofer et al proposed a simple distributed algorithm where each node makes local decisions about its transmission power and these local decisions collectively guarantee global connectivity. In a distributed protocol called COMPOW [8], the minimum common transmitting range needed to ensure network connectivity is adopted. The results shows that transmitting range has the favourable effects of maximizing network capacity, reducing the contention to access the wireless channel, and minimizing energy consumption. Optimal Geographical Density Control (OGDC) algorithm [9] addresses both sensing coverage and connectivity in wireless sensor networks. The work here computes the minimum number of nodes that must be kept awake such that both sensing coverage and connectivity are maintained. Chen et al. [10] proposed SPAN, a power saving topology maintenance algorithm for multi-hop ad hoc wireless networks which adaptively elects coordinators from all nodes to form a routing backbone and turn off other nodes' radio receivers most of the time to conserve power. Schurgers et al. [11] proposed Sparse Topology and Energy Management (STEM) approach, which exploits the time dimension rather than the node density dimension to control a power saving topology of active nodes.

As the demand for wireless services increases, efficient use of resources grows in importance. It is well known that minimizing interference using power control increases capacity and also extends battery life. In the model considered, service preferences for each user are represented by a utility function. As the name implies, the utility function quantifies the level of satisfaction a user gets from using the system resources. Game-theoretic methods are applied to study power control under this model. Game theory is a powerful tool in modelling interactions between self-interested users and predicting their choice of strategies. The problem of adjusting the transmission power of the nodes in a sensor network guaranteeing connectivity can be solved by using game theoretic framework.

Game theory 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 [12]. It is a methodology, whose scope of applications includes economics, political science, military, diplomatic, international relations, public choice, and criminology. Game theory typically assumes that all players seek to maximize their utility functions in a manner which is perfectly rational. Obviously, human players are seldom perfectly rational. When the players are computerized agents, it is reasonable to assume that the device will be programmed to maximize the expected value of some utility function and the strong rationality assumption seems to be more reasonable for machines than for people. The appropriateness of using game theory to study the energy efficiency problems and power management in WSN stems from the nature of strategic interactions between nodes. Approaches from game theory can be used to optimize node-level as well as network-wide performance by exploiting the distributed decision-making capabilities of WSN. Pricing has been studied in decentralized networks as a control variable [12, 13]. In this paper, game theory has been adopted and adjustment of transmission power of each node in a homogenous WSN considering the residual energy of the nodes is formulated as non cooperative game where nodes exchange information only with their neighbours.

The rest of the paper is orgainsed as follows. Section II examines system model. Section III, deals with the game theoretic modelling and the associated algorithm. Simulation results are given and discussed in section IV. Finally, conclusion of the work is given in Section V.

II. System Model

A wireless Code Division Multiple Access (CDMA) sensor network is considered. In this model, a two dimensional plane is considered and is assumed to have N nodes in the network area A. Square grid [14], triangular and hexagonal topology for the deployment of sensors are considered. In WSNs since depletion of battery resource changes the topology of the network; the power control should take into account the connectivity of the network topology.

By considering the nodes residual energy, those nodes with minimum residual energy can be used less frequently, thus prolonging lifetime of the node and hence the network. The Signal to Interference Noise Ratio (SINR) of the ith node is given as,

$$SINR_i = \gamma_i = (G)\frac{h_i p_i \dfrac{E_m}{E_i}}{\sum\limits_{j=1, j\neq i}^{N} h_j p_j \dfrac{E_m}{E_j} + \sigma^2} \tag{1}$$

where,

$G = W / R$ is the processing gain
W is channel bandwidth,
R is data rate
E_i is residual energy of the ith node
E_i is residual energy of the jth interfering node
p_i is the transmission power of ith node
p_j is the transmission power of jth interfering node
E_m is maximum energy of ith node
h is the path gain
σ^2 is the noise spectral density

A. Deployment of Sensors

A sensor network normally consists of a large number of nodes and the scalability is of supreme importance. Unlike nodes in the ad-hoc network, the nodes in a sensor network are static once they have been deployed. Finally, sensor nodes have limited resources such as computing capability, memory, and battery power, and it is particularly difficult to replenish or replace the battery of the sensors. Hence methods to preserve energy, as well as the monitoring of the residual energy level are crucial. The rigorous miniaturization, hardware, cost requirements, frequent topology changes and optimize use of power are vital issues and are different from normal ad hoc networks. The flexibility, scalability, fault tolerance, high sensing ability, low-cost and rapid deployment characteristics of WSNs create many new and exciting applications. A proper node deployment scheme can lessen the complexity of problems in wireless sensor network like routing, data aggregation and communication. Moreover, it can extend the lifetime of WSNs by minimizing energy consumption. Deploying smart sensors in strategically selected areas can lead to untimely detection and an increased possibility of accomplishment in fire extinguishing efforts, pollution control and climate control in large buildings.

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. For any topology the parameters such as, unreachability probability, number of interfering nodes, number of nodes needed to maintain connectivity, number of neighbouring groups are to be considered.

The number of interfering nodes for the various topologies can be obtained for a given area [15]. Considering an area of $A=100\times100m^2$, the analysis of different topologies is given Table I.

The hexagonal layout has less number of affected groups and hence dividing the sensor field into hexagonal grids ensures power control and it is also better in security and memory requirement.

As nodes share the restricted channel bandwidth, every node in the network would like to attain a higher transmitting power to increase the SINR. This ensue mutual interference among nodes, because the increase in transmitting power increases the interferences to other nodes. In order to solve the problem, an equilibrium point should be found at which the node can transmit data. So this can be abstracted as a non-cooperative game from the view of game theory in wireless CDMA sensor networks.

TABLE I
ANALYSIS OF SQUARE, TRIANGLE AND HEXAGONAL TOPOLOGIES

Parameter	Square	Triangle	Hexagon
Neighbouring groups	12	8	6
No of active nodes	308	400	52

III. GAME THEORETIC MODELLING

A game is an interactive decision making process between a set of self-interested nodes, which formally consists of the following elements [16].

A set of players, N, which may be a group of nodes or an individual node in wireless sensor networks. They are the main decision makers of the game.

A set of actions, P, available for the player i to make a decision. The payoff $\{u_1, u_2 ,.., u_i\}$resulted from the strategy profile. Payoff function expresses the level of income or utility that can be got from the game by the players and is a function of the strategy of all the players. Different strategies may lead to different benefits.

The node or the entities (decision makers) that play the game are called the players. The players take part in the game by performing particular actions or moves. The player i's possible actions is called the action space P_i of player i. Suppose that $p\in P$ is a strategy profile and $i\in N$ is a player; then $p_i\in P_i$ denote player i's action in p and p_{-i} denote actions of other players except i. Each player has preferences for the action profiles. A player is affected not only by its own actions, but also by the actions of the other players as well. A utility function u_i assigns a real value to each action profile of the game. At the beginning of the game, it is assumed that the nodes transmit with maximum power level to gather neighbour information [17]. Nash equilibrium(NE) is a fundamental concept in the theory of games and the most widely used method of predicting the outcome of a strategic interaction in the social sciences. NE is an action profile with the property that no single player can obtain a higher pay off by deviating unilaterally from power profile.

Another expression for Nash equilibrium is sometimes very useful. For any $p_i\in P_i$, the best set of participants is defined as

$$B_i\left(p_{-i}\right)=\left\{p_i\in P_i : u_i(p_i, p_{-i})\geq u_i(p_i', p_{-i})\right\}$$

for all $p_i'\in P_i$

B_i is called the "best response function" of the participants. So, Nash equilibrium can be defined to a strategy vector (a_1'…. a_n'), where $a_i'\in B_i(a_{-i}')$, for all $i\in N$

A. Utility

Utility refers to the level of satisfaction that the decision-taker (node) receives as a result of its actions. It is defined as the ratio of the expected number of bits received correctly to the energy consumed in the transmission. The utility function reveals the node preferences while considering reliability, connectivity and power consumption. In this way, the problem is viewed as an incomplete information non cooperative power and topology game, where the sensor node only has information about its own power level, neighbour number, SINR perceived from the environment and its own channel condition. If each node is assumed as a fully rational entity, NE of game theory is achieved when each node want to maximize selfish payoff and minimize the cost. When the system reaches the NE, no nodes can increase its utility any more through individual effort.

The utility of the i^{th} transmitting node is given by,

$$u_i\left(p_i, p_{-i}\right)=\frac{LR}{Fp_i}(1-2BER)^F \qquad (2)$$

where,

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

p_{-i} is the strategy profile of all the nodes but for the i^{th} node

BER is the bit error rate and is the function of SINR

B. Pricing

Each player in the game maximizes some function of utility in a distributed fashion. The game settles at Nash equilibrium if one exists. Since users act selfishly, the equilibrium point is not necessarily the best operating point from a social point of view. Hence pricing is introduced to improve efficiency and it appears to be a powerful tool for achieving a more socially desirable result. To put in a nutshell, pricing of services in wireless networks emerges as an effective tool for radio resource management because of its ability to guide user behaviour toward a more efficient operating point.

The class of pricing functions considered is linear and such a pricing function allows easy implementation. The pricing factor is a monotonically increasing function of transmit power. The pricing factor is given by,

$$K = zRp_i\frac{E_m}{E_i} \qquad (3)$$

where z is the pricing constant.

The utility of the ith node with the pricing factor included is,

$$u_i\left(p_i, p_{-i}\right) = \frac{LR}{Fp_i}(1-2BER)^F - K \qquad (4)$$

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. Alternatively, if the utility-price is quasi-concave, then the NE exists in the game with pricing. In the absence of the concavity property of the utility and the convexity of price function it is difficult to prove analytically the existence and uniqueness of a fixed point. Because utility is the ratio of efficiency to power, the benefit achieved by introducing pricing is entirely due to reduced power.

C. Power Control Algorithm with Residual Energy Check

Consider node *i* is transmitting data to the sink node. Node *i* receives the sum of interference power $\sum_{j=1, j\neq i}^{N} h_j p_j$ from sink node. 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 and the transmitted power of the ith node is given by

$$p_i = \arg\max_{p_i \in P_i} \{u_i\left(p_i, p_{-i}\right)\} \qquad (5)$$

After each iteration, a node power level change influences the overall topology of the network which is taken into account by the other nodes when optimizing their utility function. 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. It is not possible to recharge the batteries or replace them. 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 check algorithm is used [18]. 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 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.

The algorithm is as given below,

Maximum energy of the node, $E_m = 5$ J
Check network connectivity
  If connected
Perform residual energy check
calculate $u_i\left(p_i, p_{-i}\right)$ *#using equation (4)*
else
  $u_i\left(p_i, p_{-i}\right) = 0$
end if
  $u_i(m) = u_i\left(p_i, p_{-i}\right)$
Estimate the transmit power
  $p_i = \arg\max_{p_i \in P_i} \{u_i\left(p_i, p_{-i}\right)\}$
Transmit the data with estimated optimal power
end for

The maximum energy of the node is assumed to be 5J. The remaining energy of the node after every transmission is known as the residual energy. The inclusion of residual energy check scheme reduces the achievable transmission range of the node which is directly proportional to the transmission power. Hence the lifetime of the network is considerably improved. The optimal transmit power is estimated and the data is transmitted with estimated optimal power. For this, ith nodes residual energy is determined.

The residual energy (E_0) of the ith node is given by

$$E_0 = E_{ini} - E_t \qquad (6)$$

where
E_{ini} is the initial energy of the node
E_t is the energy consumption of the node in the previous round

The lifetime of the sensor node is given by

$$T = \frac{E_0}{p_i} \qquad (7)$$

D. Existence of Nash Equilibrium for the proposed game

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

From equation (1)

$$\frac{\partial \gamma_i}{\partial p_i} = f(\gamma_i) = \frac{W}{R}\frac{h_i \frac{E_m}{E_i}}{\sum_{j=1, j\neq i}^{N} h_j p_j \frac{E_m}{E_j} + \sigma^2}$$

From equation (4)

$$\frac{\partial u_i\left(p_i, p_{-i}\right)}{\partial p_i} = -\frac{LR}{Fp_i^2}\left(1-e^{-\gamma_i}\right)^F - zR\frac{E_m}{E_i} + \frac{LR}{p_i}\left(1-e^{-\gamma_i}\right)^{F-1} e^{-\gamma_i} f(\gamma_i)$$

and taking the second-order derivative of $u_i\left(p_i, p_{-i}\right)$ with respect to p_i yields $\frac{\partial^2 u_i\left(p_i, p_{-i}\right)}{\partial p_i^2} < 0$

Since $\frac{\partial^2 u_i(p_i, p_{-i})}{\partial p_i^2} < 0$, $u_i(p_i, p_{-i})$ is concave in p_i. This proves that NE exists in the game with pricing and that they are Pareto superior compared to the equilibrium of the game with no pricing.

IV. Simulation Results and Discussion

The square [14], triangular and hexagonal topologies were considered to determine the deployment scheme that provides better connectivity and power control. The simulation parameters used are tabulated in Table II.

TABLE II
SIMULATION PARAMETERS

Simulation Parameters	Description
Transmit power{P_{min}:P_{max}}	1-100mW
Channel Bandwidth	1MHz
Data rate	20kbps
Path loss component	2
Modulation technique	DPSK
Noise variance	5×10^{-15}

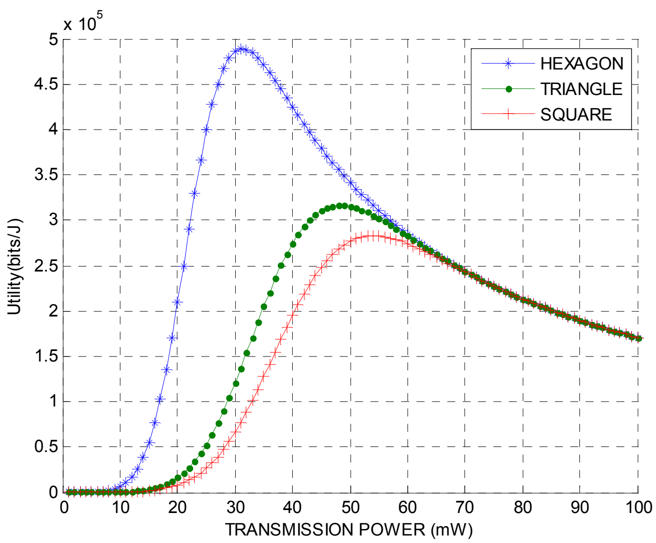

Fig.1 Utility of the game without residual energy check scheme

The utility as a function of transmit power for all the three deployment schemes, without residual energy check is shown in Fig.1. The square and triangular deployment schemes provide the maximum utility of 2.83×10^5 bits/joule and 3.16×10^5 bits/joule at transmission power of 54mW and 48mW respectively. A maximum utility of 4.88×10^5 bits/joule is achieved at the minimum transmission power of 31mW for hexagonal deployment scheme. Hexagonal deployment provides 72% increase in utility and 43% reduction in transmission power as compared to square grid deployment and also provides 54.4% increase in utility and 35.4% reduction in power when compared with triangular deployment scheme.

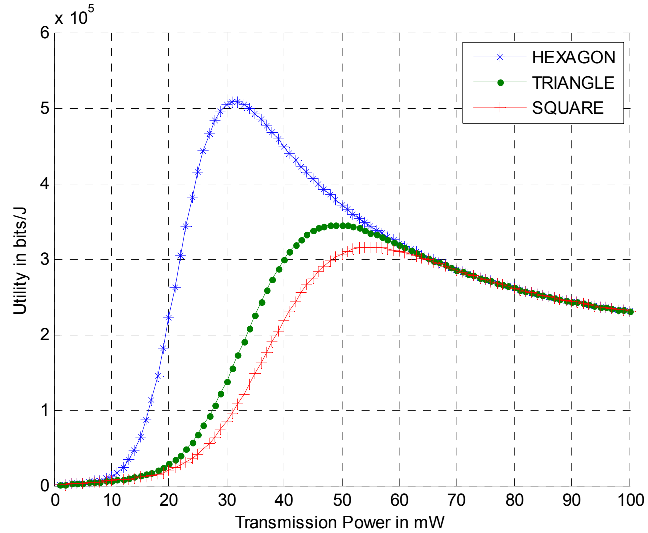

Fig.2 Utility of the game with pricing without residual energy check scheme

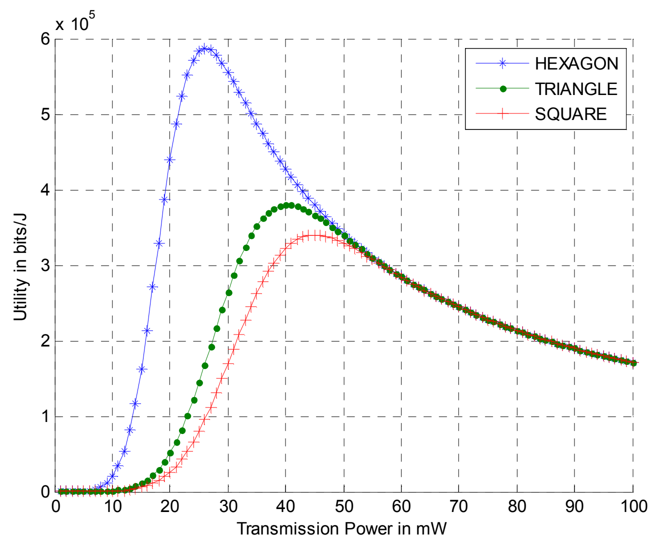

Fig.3 Utility of the game with residual energy check scheme

Each sensor node tries to maximize its own utility by adjusting its own power as given by the utility function. The utility function from a sensor node's viewpoint considers the interference it gets from other nodes; on the other hand, it ignores the fact that this node imposes on itself in terms of drainage of energy. Pricing is effectual in regulating this externality, as it encourages the nodes to use resources more competently. If a particular node in the network tends to increase its transmit power such that it creates interference to the other nodes, then the effect of pricing decreases the utility of that node by pricing factor K and increases the utility of the other nodes by pricing factor K. From Fig.2 it is inferred that, hexagonal deployment scheme with pricing provides a maximum utility of 5.1×10^5 bits/joule at the transmission power of 31mW. An increase in utility by 5% is obtained by considering the pricing strategy.

The utility of the game considering residual energy of the node is given in Fig.3. The energy check algorithm effectively reduces total transmitting power of nodes. Hexagonal deployment provides maximum utility compared to other counterparts. For the hexagonal deployment with residual energy check a maximum utility of 5.8×10^5 bits/joule is achieved for a transmission power of 26mW.

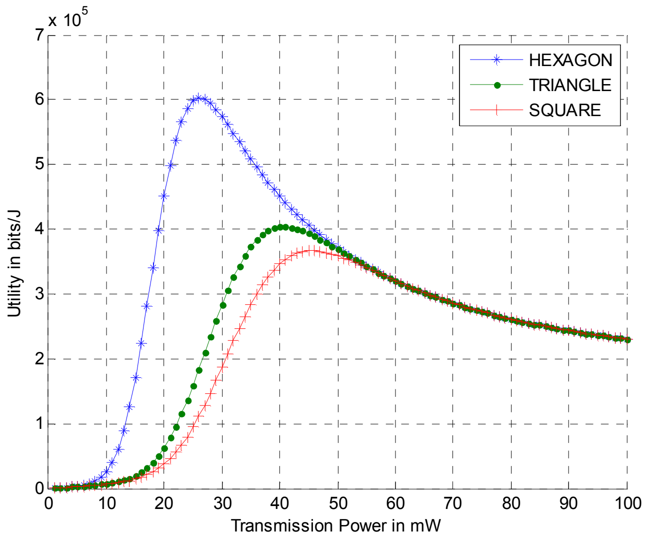

Fig.4 Utility of the game with pricing with residual energy check scheme

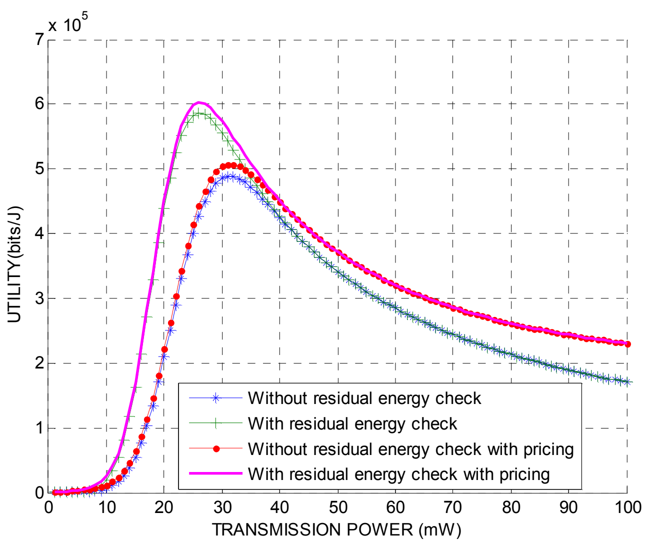

Fig.5 Comparison of utility considering hexagonal deployment

From the Fig.4 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 6.1×10^5 bits/joule for the minimum transmission power of 26mW.

Further, it is inferred from Figs.1- 4 that the hexagonal deployment method attains maximum utility and minimum transmission power for all the cases. So, the hexagonal deployment scheme is considered for analysis in the remaining part of the paper. From the Fig.5 it is shown that there is an increase in utility of 19% and decrease in transmission power of 16% by residual energy check scheme when compared to without residual energy check. It is also shown that the residual energy check scheme with pricing offers better utility (approximately 5% increase in utility) compared to the game without pricing for the same transmission power.

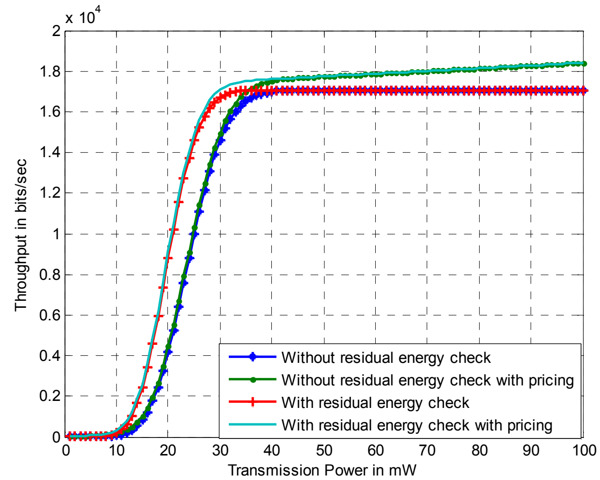

Fig.6 Comparison of throughput

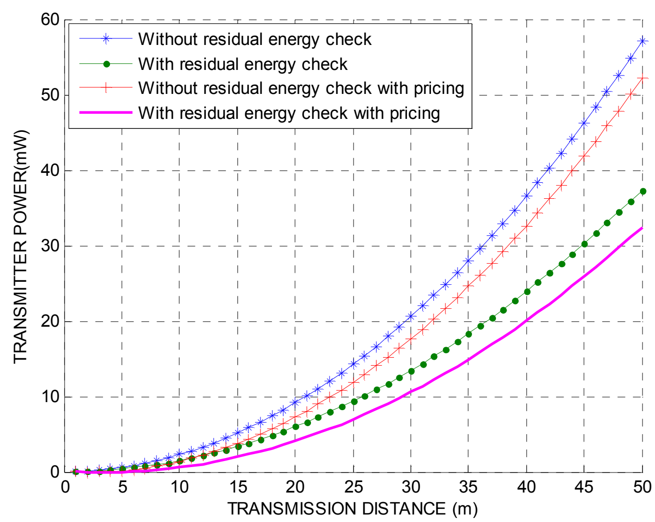

Fig.7 Comparison of transmitter power

As shown in Fig.6, the throughput of the game with residual energy check with pricing is the highest for minimum transmission power. Considering the tranmission power of 26mW, for residual energy check with pricing yields an increase in throughput of 36% as compared to without residual energy check with pricing.

The variation of transmitter power of the node with transmission distance for with and without residual check schemes is shown in Fig.7. This figure demonstrate that residual energy check scheme considerably saves the transmitter power, approximately 33%, 35%, and 35% for the distance of 20m, 35m and 50m respectively when compared to that of without residual energy scheme. It is also observed that residual energy check scheme with pricing saves approximately 33%, 17% and 11% transmission power compared to the game without pricing for the same distances taken for analysis.

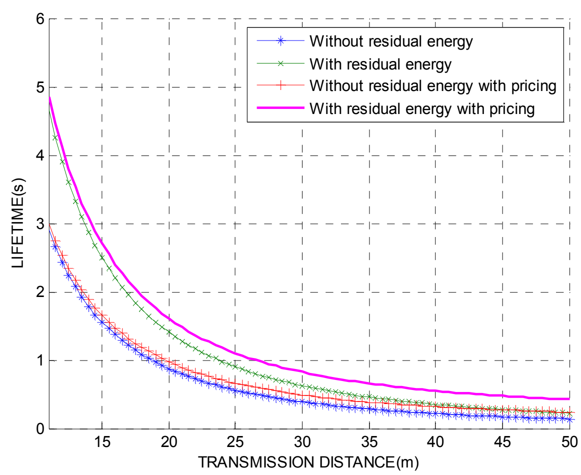

Fig.8 Lifetime analysis

Fig.8 explains the impact of transmission distance on lifetime of the node. 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 residual energy check scheme with pricing increases approximately 14% and 40% than that of residual energy check scheme without pricing for the same distances considered.

V. Conclusion

A game theoretic model with pricing for power control taking into account the residual energy of the nodes in a homogeneous sensor network considering various deployment schemes have been analysed in this paper. The connectivity is taken into consideration and the existence and uniqueness of the Nash Equilibrium 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 behaviour 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 extends the network lifetime efficiently.

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