Utility based Power Control with FEC in Hexagonally deployed WSN

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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 WSN and to maintain the battery life of the sensor node and in turn the sensor network. Error control coding (ECC) schemes can improve the system performance and has an impact on energy consumption. This paper analyses a game theoretic model with pricing for power control in a sensor network considering ECC for random, square, triangular and hexagonal deployment schemes. The performance of the proposed power control scheme with RS and MIDRS code for WSN is evaluated in terms of utility, and energy consumption. Simulation results show that, for hexagonal deployment scheme, with the inclusion of ECC, 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, Deployment schemes*

1. Introduction

The recent advances in wireless communication and micro electronics over the last few years, have let to 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]. 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 in various applications such as predicting events that threaten species and environments, including gathering information from animal habitats, in volcanic activity monitoring, flash-flood alerts and environmental monitoring. 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 [2].

Topology control minimizes the contention when accessing the wireless channel and reduces the energy consumption. 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 [3]. In [4] 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 [5], 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 [6] 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. [7] 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. [8] 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.

Further in wireless environments, multipath fading strongly impacts the communication in WSN. Multipath fading increases the possibility of signal cancellation which leads to higher packet loss and therefore resulting in more power consumption. As sensors are used for high end applications, the data has to be reproduced with extremely low bit error rate (BER). To maintain the BER within a limit, either transmit signal power has to be increased or error control coding (ECC) can be used. ECC reduces the required transmitted signal energy because of its coding gain. Energy constraint transmission issue of WSN makes forward error correction (FEC) a popular error correction technique to be used in such networks reducing the frame error rate and consequently the number of retransmissions. A system with FEC can provide a reliability using less power than a system without FEC [9]. Therefore proper error control coding can save the power required for communication of the information bits.

Researchers have explored the sensor node energy with different error control codes as well as different modulation schemes. Chouhan et al.[10] have proposed a framework for energy consumption based design space exploration. Using this framework, the authors have explored various ECCs and observed that using ECC saves energy as compared to uncoded data transmission. Most of the pioneering research in the area of energy-constrained communication has focused on transmission schemes to minimize the transmission energy per bit. Howard et al. [11] have analyzed the distance at which an ECC becomes energy efficient for different environment and operating frequencies. Among the most popular FEC's today Reed Solomon (RS) code is widely used [12] and is considered to be the best choice for WSN.

Game-theoretic methods are applied to study power control in wireless networks. Game theory [13] 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. 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 [14]. In this paper, game theory has been adopted and adjustment of transmission power of each node in a homogenous WSN with FEC is formulated as non cooperative game.

The rest of the paper is organised as follows. Section 2 examines system model and section 3 deals with ECC. Section 4, deal with the game theoretic modelling and the associated algorithm. Simulation results are given and discussed in section 5. Finally, conclusion of the work is given in Section 6.

2. 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. Random, square triangular and hexagonal topology for the deployment of sensors are considered. 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,

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

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

2.1 Deployment of sensors

A sensor network normally consists of a large number of nodes and the scalability is of supreme importance. 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. 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]. 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.

3. Error Control Coding for WSN

3.1 Reed Solomon coding

Reed Solomon (RS) codes are a systematic linear block code having maximum energy efficiency in proper channel conditions. RS code is generally represented as RS (n_{RS},k_{RS},d_{min}), and $d_{minRS}=2t_{RS}+1$.
where

n_{RS} is the length of the code word,
k_{RS} is the number of information symbols,
t_{RS} is the maximum number of correctable errors
d_{minRS} is the minimum hamming distance of the code

For PSK modulation BER is expressed as [16]

$$BER_{uncoded} = \frac{1}{b}\operatorname{erfc}\left(\sqrt{b\gamma}\sin\left(\frac{\pi}{m}\right)\right) \tag{2}$$

$$BER_{coded} = \frac{1}{n_{RS}}\sum_{j=t_{RS}+1}^{n_{RS}}\binom{n_{RS}}{j}p_c^{\,j}(1-p_c)^{n_{RS}-j} \tag{3}$$

where

m is the order of modulation
b is the number of bits that make a symbol
γ is the signal to interference noise ratio
p_c is the channel symbol error probability

3.2 Multivariate Interpolation Decoding RS (MIDRS) Code

In MIDRS [17], *M*-RS codes are transmitted together and decoded using (M + 1) variate interpolation. The encoding is of complexity order of *M*-RS encoders. The MID algorithm attempts to list-decode up to

$$t_{MIDRS} = Mn_{RS}\left(1-\frac{k_{RS}}{n_{RS}}^{\left(\frac{M}{M+1}\right)}\right) \tag{4}$$

where t_{MIDRS} is the maximum number of correctable errors for MIDRS.

The advantages of multivariate interpolation algorithm are that the error-correction radius t_{MIDRS} of the MID algorithm is greater than t_{RS} for all rates. While the Bleichenbacher, Kiayias, and Yung (BKY) and by Coppersmith and Sudan (CS) decoders of RS codes simply fail for certain error patterns, the MID algorithm offers a graceful degradation option. The probability of decoding failure is significant for the CS decoder, but it is often negligible for the MID algorithm.

For PSK modulation BER is expressed as

$$BER_{coded} = \frac{1}{n_{MIDRS}}\sum_{j=t_{MIDRS}+1}^{n_{MIDRS}}\binom{n_{MIDRS}}{j}j(1-p_c)^{n_{MIDRS}-j}p_c^{\,j} \tag{5}$$

where

n_{MIDRS} is the length of the code word for MIDRS,
k_{MIDRS} is the number of information symbols for MIDRS,

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4. 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 [18].

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. 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.

4.1 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,

$$u_i\left(p_i, p_{-i}\right)=\frac{LR}{Fp_i}(1-2BER_{coded})^F \qquad (6)$$

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_{coded} is the bit error rate

4.2 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, 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,

$$K = zRp_i\frac{E_m}{E_i} \qquad (7)$$

where z is the pricing constant.

The utility of the i^{th} node with the pricing factor included is,

$$u_i\left(p_i, p_{-i}\right)=\frac{LR}{Fp_i}(1-2BER_{coded})^F - K \qquad (8)$$

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.

4.3 Power Control Algorithm

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 i^th^ node is given by

$$p_i = arg\,\max_{p_i \in P_i}\{u_i\left(p_i, p_{-i}\right)\} \qquad (9)$$

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 [19]. 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 the number of interfering nodes for each
        deployment scheme
        calculate $u_i(p_i, p_{-i})$
else
        $u_i(p_i, p_{-i}) = 0$
end if
        $u_i(m) = u_i(p_i, p_{-i})$
Estimate the transmit power
            $p_i = \arg\max_{p_i \in P_i}\{u_i(p_i, p_{-i})\}$
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.

5. Simulation Results and Discussion

The random, square [20], triangular and hexagonal topologies were considered along with RS and MIDRS coding to determine the deployment scheme that provides power control. The simulation parameters used are tabulated in Table 1.

Table 1: Simulation parameters

Simulation Parameters	Description
Network areas (m^2)	100x100
Number of nodes	100
Transmit power{P_{min}:P_{max}}	1-100(mW)
Channel Bandwidth	1MHz
Data rate	20kbps
Path loss component	2
Modulation technique	QPSK
Noise variance	5×10^{-15}

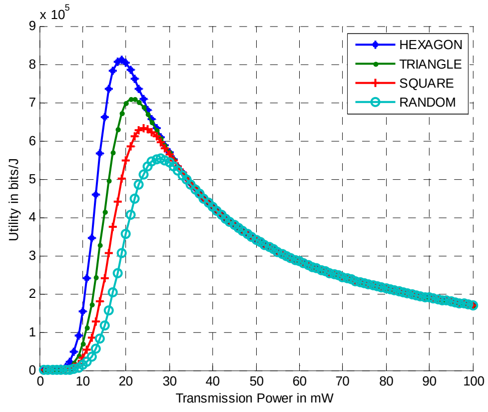

Fig.1 Utility of the game with RS coding and without pricing

The utility is observed as a function of transmit power for all the four topologies on considering RS coding and is shown in Fig.1. When the area is analysed as random topology a maximum utility of 5.549×10^5 bits/joule is achieved for a transmission power of 28mW. For the square and triangular topology a maximum utility of 6.324×10^5 bits/joule and 7.104×10^5 bits/joule are achieved for a transmission power of 24mW and 22mW respectively. For the hexagonal topology a maximum utility of $8.13\times10_5$ bits/joule is achieved for a transmission power of 19mW. The utility is the maximum for hexagonal topology when compared to other topologies. The transmit power is also the least for hexagonal topology. Sensor deployed when considering hexagonal deployment with RS coding provides 29% increase in utility as compared to square topology for 21% reduction in power. It provides 15% increase in utility as compared to triangular topology for 14% reduction in power.

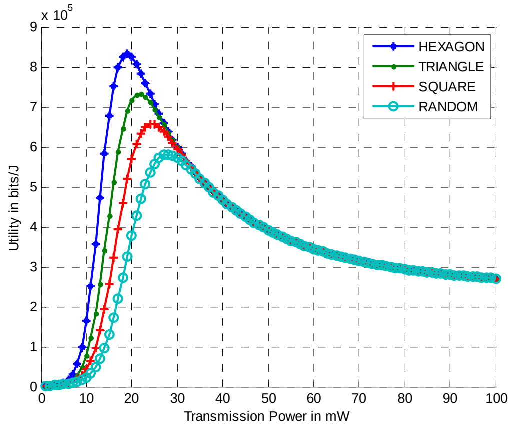

Fig.2 Utility of the game with RS coding and with pricing

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 8.4×10^5 bits/joule at the transmission power of 19mW. An increase in utility by 3% is obtained by considering the pricing strategy.

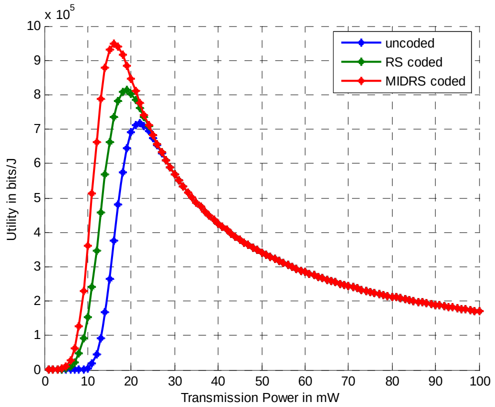

Fig.3 Utility of the game without pricing considering hexagonal deployment

The utility as a function of transmit power for hexagonal deployment scheme, for uncoded, RS coded and MIDRS coded is shown in Fig.3. The energy check algorithm effectively reduces total transmitting power of nodes. A maximum utility of 7.104×10^5 bits/joule is achieved at the minimum transmission power of 22mW for uncoded hexagonal deployment scheme. RS code with hexagonal deployment provides 29% increase in utility and 22% reduction in transmission power as compared to uncoded scheme. MIDRS provides 16% increase in utility and 11% reduction in power when compared with RS coded hexagonal deployment scheme.

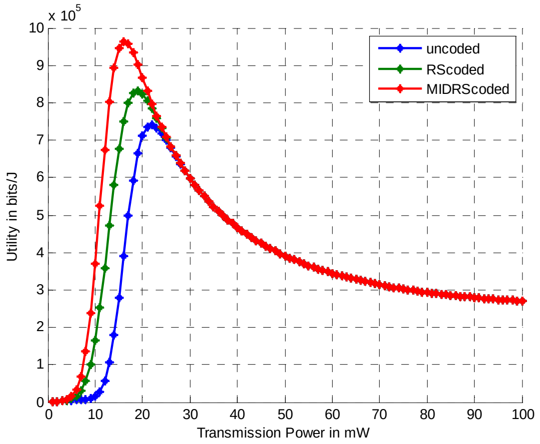

Fig.4 Utility of the game with pricing considering hexagonal deployment

From Fig.4 it is inferred that, hexagonal deployment scheme with pricing provides a maximum utility of 7.324×10^5 bits/joule at the transmission power of 22mW. An increase in utility by 4% is obtained by considering the pricing strategy. MIDRS code with pricing provides an increase in utility by 34% compared to uncoded scheme.

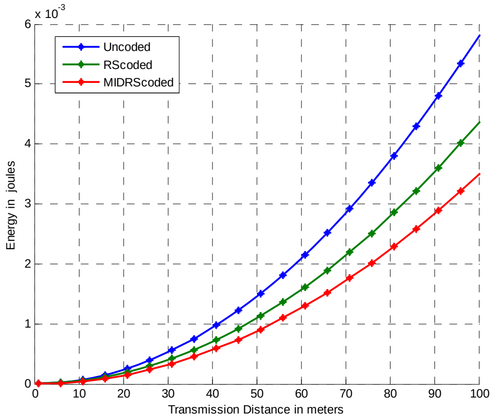

Fig.5. Energy consumption considering hexagonal deployment

The energy consumption of uncoded, RScoded and MIDRS coded WSN with hexagonal deployment scheme is shown in Fig.5. From this figure it is evident that as the distance increases the energy consumption of the node gradually increases. RS coded and MIDRS coded schemes reduce the energy consumption by 25% and 39% compared to uncoded scheme respectively for a distance of 50m. The decrease in energy consumption is due to the error correction codes employed which reduces the number of retransmissions.

6. Conclusions

A game theoretic model with pricing for power control taking into account the residual energy of the nodes in a sensor network considering random, square, triangular and hexagonal deployment schemes have been analysed in this paper. The maximum utility is obtained at minimal transmission power for hexagonal deployment scheme with MIDRS coding. 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.

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