AN ADAPTIVE THROUGHPUT, SPECTRAL, ENERGY EFFICIENT AND FAIR NETWORK CONFIGURATION IN PERVASIVE ENVIRONMENT

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ABSTRACT

In this work, we propose a mechanism in which power consumption in a sensor network can be reduced greatly by taking into account the fairness factors and to increase the probability of nodes for successful packet transmission with lowest possible Signal to Noise Ratio (SNR) in a crowded environment. In other words we propose a high throughput and spectrally efficient network. The power consumption of the network reduces drastically when the clustered approach is adopted, which has been confirmed using the Friss transmission formula. Here, we have used analytical expressions from renewal reward theorem to deduce network throughput, probability of collisions and back-off periods upon collision in a random multiple access environment. Using those expressions we have made an analysis on network throughput, probability of collisions, bandwidth availability per node and estimation of back-off intervals upon collisions. The total number of nodes in the network is kept constant for observational purposes. The number of clusters has been varied to take observation of network throughput, probability of collisions, bandwidth availability per node and estimation of back-off intervals upon collisions. The analytical results obtained show that the power requirement of the network reduces drastically as the number of clusters increases.

KEYWORDS

CSMA/CA, sensor network, throughput, collision probability, backoff time, power reduction ratio, clustered network approach

1. INTRODUCTION

An ad-hoc network is a network which comprises of a number of nodes which are self dependent and do not associate with any infrastructure based network. Ad-Hoc networks provide a variety of services such as sharing of data and distributed services while sensor networks are used in consumer as well as industrial applications such as process monitoring and control, environment and habitat monitoring, healthcare applications home automation and traffic control [1]. They can be deployed anywhere and their cost of implementation is low. An important characteristic of ad-hoc networks is that they can configure themselves without any centralized control; a feature which distinguishes itself from other networks which have infrastructure dependency. Taking this

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into consideration we are proposing mechanisms that avoid problems associated with single point failures and infrastructure based dependencies in sensor networks.

In this work, we have focused on the identification of problems in both ad-hoc and sensor networks and provide such as low link throughput, power consumption, dependency of nodes on one particular super node. In sensor networks, we need cluster-heads and pre-defined network configuration among the clusters [13]. This often leads to common node failure. For e.g. if a sensor head fails then no sensor belonging to it can forward the data. So to eliminate this centralized dependency we have suggested a solution in which each node gets an opportunity to act as the sensor head there by using distributed architecture. We describe methods to optimize power required for transmission. Note that battery power is very important for a sensor as its life is equal to the life of its battery. There are some related work [14-17] which deals with efficient use of energy through clustering technique. Here we propose solutions on how to increase throughput of such networks taking into account the fairness factors.

As the number of nodes in an ad-hoc network increases the probability of any particular node to successfully communicate with acceptable bit error reduces significantly. The waiting period in the underlying random access protocols tends to increase drastically [2]. Efficient switching techniques are necessary to tackle such type of problems. In light of such problems we have formulated measures to provide simple realizable solutions to tackle such problems without bearing much cost and complexity in network design. We present here a mechanism in wireless ad-hoc/sensor networks that reduces power consumption of the network drastically and at the same time increase throughput significantly. Some of the relevant literatures are [2, 3, 4].

2. Background Principles

Ad-hoc networks using wireless communication are generally mobile which implies that the primary energy resource is the battery. When the number of sensor nodes increases, the network topology needs to be updated more frequently. If the frequency of a route is comparable to the frequency of updates, then considerable amount of resource is drained. When the nodes of the network are mobile the problem is compounded. In order to conserve power and spatial reuse, the nodes reduce their transmission range.

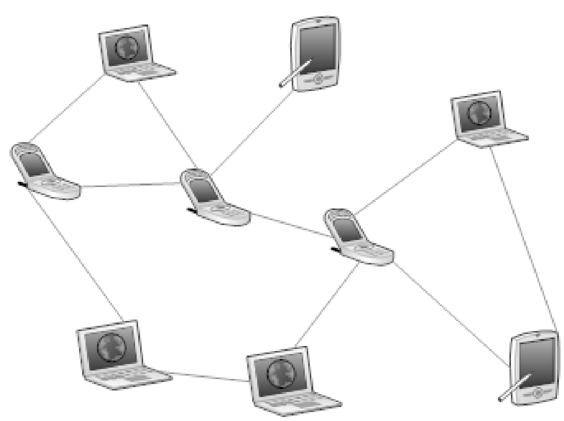

Figure 1: Conventional Ad-Hoc Network

This, however, increases the hop count and hence there can be long delays for the packets to reach their destination [5, 6]. When the range is too low, the network can be disconnected due to increase in hop count. Therefore, the range must be sufficiently high to keep the network connected. Apparently if the operational area of the network is kept fixed then the transmission range is a function of the number of nodes in the network. There are many factors which cause inefficiencies in a conventional ad-hoc network which increase tremendously when the number of nodes increases [1, 6]. In light of the factors, we have made an attempt to propose a mechanism in which all the problems can be addressed in a simple manner at a low cost of computation. The diagram of a conventional ad-hoc network is shown in the Figure 1.

In ad-hoc networks, as the number of communicating node increases the probability that a node will able to send packets decreases and in order to complete a successful transmission without collision causes significant delay. So in order to achieve good link throughput the number of nodes have to be reduced somehow. This is not a solution as it would lead to denying connection to users who might be in an emergency. One way in which this problem can be tackled is to reduce the transmission power of the nodes. This directly increases the reuse factor as greater number of users can be accommodated in the available spectrum. This also drastically increases throughput of the network. But the option of reducing the transmission range of the nodes generates another problem which being the network overhead, ultimately reduces the packet efficiency.

3. THE PROPOSED SENSOR NETWORK USING THE CLUSTERED APPROACH

Wireless sensor networks are those in which autonomous sensors monitor physical and environmental conditions. The sensors pass their data cooperatively through the network to a main location. The sensor networks are similar to ad-hoc networks and have no infrastructure. The sensors are tiny and have very low processing power and memory. In sensor network application, we need cluster-heads and pre-defined network configuration among the clusters. At present the networks are bidirectional, enabling also to control the activity of the sensors. Energy is the scarcest resource of wireless sensor networks and it determines the lifetime of the sensor network.

Our main approach is to find an optimization of throughput, range reusability such that the nodes in the network are able to transmit maximum number of packets with minimum power consumption with reliability of communication being one of the foremost matters of importance. Our main proposal is that the network be divided into clusters with each cluster containing a part of nodes of the whole network. The range of each node is confined to the cluster boundaries and each one is identified as belonging to a particular cluster. Among all the nodes in a cluster there exists a special node which has a range higher than those belonging to that cluster and is called the primary node. The rest are called secondary nodes. Thus the node distinction comes from the range variability concept. Similarly all the clusters have the same story. The primary node of each cluster communicates with the primary nodes of its neighbouring clusters and secondary nodes of its own cluster and not with anyone else. The primary nodes make inter-cluster communication possible and thus functions as a gateway forwarding packets of secondary nodes of its own cluster. The primary nodes receive information from neighbouring primary nodes and relay the relevant information to its secondary nodes. This approach takes care of the network overhead problem that arises due to the breaking up of the network into clusters. It happens because the primary nodes come into being when distance between the communicating nodes is high and reduce the hop count substantially.

Each cluster has lesser number of nodes in comparison with number of nodes in the entire network and hence the probability that a node will able to generate a packet and its successful delivery will increase. Apparently, the bandwidth available per user (node) will increase which leads to enormous increase of throughput of the whole network when the throughput of all the clusters are taken in as a whole. Therefore, increasing the number of clusters increases the throughput significantly. Some of the relevant literatures are [3] [4].

The main problem in implementing this scheme is the reluctance of secondary nodes to become the primary node as it will have to forward packets of other node, thereby, hindering the transmission of its own packets. So we have suggested all nodes in the cluster would take turns in functioning as the primary node. This is accomplished by using a Voting Request Algorithm (VRA).

The steps of the algorithm are:-

1. All nodes would advertise their remaining battery power and processor utilization at regular intervals.
2. All other nodes would receive it and find out the node with the fittest remains.
3. All the nodes will share the fittest node information with all other nodes.
4. Node receiving maximum vote will be selected as the next cluster-head (primary node) and the current head will hand over the charges to the new head.

Thus, there would be a periodic rotation of cluster-heads which would eliminate the problem of single node failure and dependency on infrastructure based network.

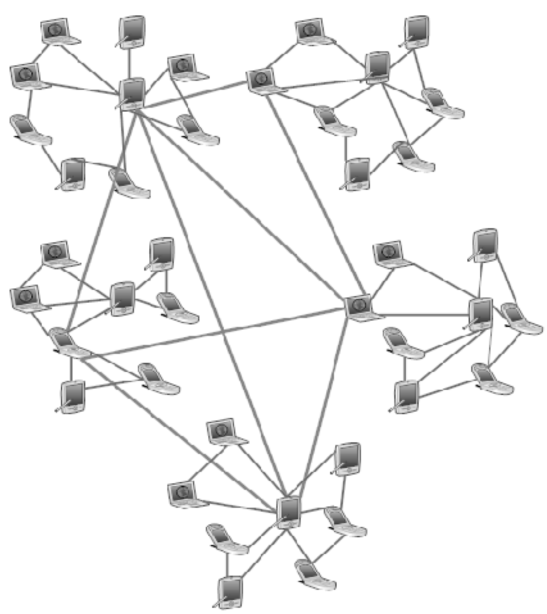

Figure 2: Suggested Network Topology

The protocol used at the link layer to manage communications is CSMA/CA. The 802.11 specification, distributed random access standard called the distributed coordination function (DCF) is used in our network for multiple accesses [7, 8]. The DCF random access procedures are based on CSMA/CA mechanisms. The physical layer standard used for communication is 802.11a. Different band of frequencies are used for intra and inter cluster communication to prevent interference between primary and secondary for inter traffic. The frequency band used for secondary traffic is same for all the clusters. The primary nodes use a separate band from the secondary nodes. All the primary nodes use same frequency for inter cluster communication and each primary node communicates only with the neighbouring primary nodes to avoid interference. This increases the spectral efficiency. When specified that each node is identified as belonging to a particular cluster means that each cluster is assigned a particular range of IP addresses. In the network, there would be a pre-defined number of clusters. The primary node will possess all the IP addresses belonging to that cluster. There will be two categories of IP address. The first category is used to identify the primary node and to carry inter-cluster traffic while the second category to carry intra-cluster traffic. This means that only the primary node will have two categories of IP addresses for inter and intra cluster communication while the secondary nodes have one IP address for intra cluster communication. The nodes that arrive afterwards in a particular cluster are allocated IP address from the primary node for intra cluster communication. The distance vector routing [12] protocol will be used for secondary traffic routing and On-demand routing for primary traffic routing which is based on the flooding mechanism [11]. Each node will have two routing protocols for inter and intra cluster communication. The primary node will be having two routing protocols activated at the same time and the secondary nodes will have one routing protocol active and the second inactive.

When there is an exchange of node status from primary to secondary or vice-versa in a particular cluster, then that particular cluster will be invisible momentarily for other primary nodes present in the network. As a result, the primary traffic will be interrupted but the secondary traffic will continue as usual. When a particular node moves from one cluster to the other then it will have to surrender its IP address to the primary node of the cluster in which it belonged previously. When a primary node detects a newly arrived node, it allocates an IP address to it and updates its secondary routing table. The period during which a node moves from one cluster to another, the entire communication whether uplink or downlink is completely terminated. However, the node can resume communication and re-establish itself to its previous state if an application for the same purpose is installed in it.

In sensor networks, energy is the scarcest resource and hence preserving it should be the primary objective. The life of a wireless sensor node depends upon the life of its battery. Because of the division of networks into clusters the distance between the transmitter and receiver has become much lesser and the transmission range reduced. Correspondingly, the power requirement of the nodes will be reduced according to the inverse square law of power variation with distance as well as the power received by a node will be much higher in comparison to the conventional approach.

Thus we have proposed a mechanism which improves the link throughput of the network, reduces power consumption of the nodes, improves power gain and hence enhances the lifetime of the nodes, improves the fairness of the system such that no node is over burdened and increases the reliability of the network. These features are obtained by dividing the network into clusters.

4. MATHEMATICAL ANALYSIS

In this section, we specify the mathematical tools [8, 9, 13] and the expressions which we shall use to calculate the results to demonstrate the validity of the claims that we have made in previous section.

4.1. Throughput

We shall assume that the network is busy all the time and nodes are exchanging packets with one another. We also assume that the back off time is exponentially distributed with mean $1/\beta$. Therefore, the average back off time is $1/\beta$.

Let us consider T_0 as the packet over head time then in 802.11 standard :

$$T_o = \text{RTS} + \text{CTS} + \text{ACK} + 3\text{SIFS} + \text{DIFS}. \quad (1)$$

where RTS(Request to send), CTS(Clear to send), ACK(Acknoledgement), SIFS(Short Interframe Space) and DIFS (Distributed Coordination Function Interframe Space). If T_c be the time spent in a collision before next backoff period then in 802.11 standard:

$$T_c = \text{RTS} + \text{DIFS}. \quad (2)$$

Now, let us consider ***n*** be the number of nodes, ***r*** the data rate, *L* be the packet length used by all the nodes, δ as slot time and β as the parameter of exponential backoff duration. Since we have assumed that the backoff period is exponentially distributed the residual and fresh backoff times are also exponentially distributed. Hence the time until the first backoff time is completed is exponentially distributed with mean $1/n\beta$. The collision probability (γ) in a distributed random acess standard distributed coorination function (DCF) is given by [6]:

$$\gamma = 1 - e^{-(n-1)\beta\delta} \quad (3)$$

Now the mean time between successive renewal times is; the residual or fresh backoff time, packet overhead time and payload time if there is a successful transmission, collision time if there is a collision stated mathematically [6]:

$$\text{T} = \frac{1}{n\beta} + (1-\gamma)\left(\frac{L}{r} + T_0\right) + \gamma T_c$$

Hence, network throughput is given by [6]:

$$\Theta(\gamma, \beta) = \frac{(1-\gamma)L}{\frac{1}{n\beta} + (1-\gamma)\left(\frac{L}{r} + T_0\right) + \gamma T_c} \quad (4)$$

Now the throughput is maximized for:

$$\beta = \frac{1}{2nT_c}\left(\sqrt{1 + \frac{4nT_c}{(n-1)\delta}} - 1\right) \quad (5)$$

4.2. Back off Time

Let K be the maximum chances for a packet to attempt transmission before being discarded and b_K the mean back off duration of a node after k^{th} collision, then the random amount of cumulative backoff time between successive successful packet transmissions or packet discards will be:

$$b_0 + \gamma\left(b_1 + \gamma\left(b_2 + \gamma\left(\cdots\left(\cdots\left(\gamma b_K\right)\right)\right)\right)\right).$$

The number of attempts a node makes between successive successful packet transmissions or packet discards is given by:

$$1 + \gamma + \gamma^2 + \cdots\cdots + \gamma^K .$$

Therefore, β the attempts parameter becomes:

$$\beta = \frac{1 + \gamma + \gamma^2 + \cdots\cdots + \gamma^K}{b_0 + \gamma b_1 + \gamma^2 b_2 + \cdots\cdots + \gamma^K b_K} \quad (6)$$

Assuming that K = ∞ and *m* such that:

$$b_K = \left(\frac{2^k CW_{\min} - 1}{2}\right).\delta, \qquad \text{for } 0 \le k \le m-1 \text{ and}$$

$$b_k = \left(\frac{2^m CW_{\min} - 1}{2}\right)\delta \qquad \text{for } k \ge m \text{ then:}$$

$$\beta = \frac{2(1-2\gamma)}{(1-2\gamma)(CW_{\min}-1) + \gamma CW_{\min}\left[1-(2\gamma)^m\right]} \times \frac{1}{\delta} \tag{7}$$

The back off time is given by: $$\frac{1}{\beta} = \delta.\frac{(1-2\gamma)(CW_{\min}-1) + \gamma CW_{\min}\left[1-\left(2\gamma^m\right)\right]}{2(1-2\gamma)} \tag{8}$$

4.3. Power Saving Formula

Let P_t be the transmitted power, P_r be the received power, A_{er} the receiving antenna aperture, A_{et} be the transmitting antenna aperture and G_t as transmitting antenna gain. Then according to Friss transmission formula the ratio of power received to power transmitted is given by [10]:

$$\frac{P_r}{P_t} = \frac{A_{et}A_{er}}{\lambda^2 R^2} \tag{9}$$

When the network is divided into clusters *R* becomes *R / M*, where *M* is the number of clusters in the axis of transmission. The power ratio of the clustered network is:

$$\frac{P_{rc}}{P_{tc}} = \frac{M^2 A_{et}A_{er}}{\lambda^2 R^2} \tag{10}$$

Therefore the power increases by a factor:

$$\frac{P_{rc}}{P_{tc}} = M^2 \frac{P_r}{P_t} \tag{11}$$

Therefore the power with which a node has to transmit for successful packet delivery is reduced by $1/M^2$ times in comparison with the conventional type network as $P_{tc} = P_t/M^2$

5. Results and Discussion

The number of nodes is kept fixed at 600. Maximum number of nodes in one cluster assumed to be 20. We also assume that the number of nodes in all the clusters is equally distributed. We have analytically computed the network throughput, backoff time, collision probability, bandwidth availability per using the formulas stated in the previous section. The observations were made by varying the number of nodes. Since the total number of nodes in the network has been kept fixed varying the number of nodes essentially means increasing the number of clusters.

The values considered for the following variables during computation are:

Data rate (r)=18 MBPS, packet length used by all the nodes (L) =1500 Bytes, slot time (δ) = 9µs, packet overhead time (T_0) =598µs, T_c :RTS + DIFS =240 µs, CWmin: = 32.

5.1. Collision Probability

The collision probability is calculated using eqn.(3). We assume that the throughput is maximized, hence, β is calculated using eqn.(5).

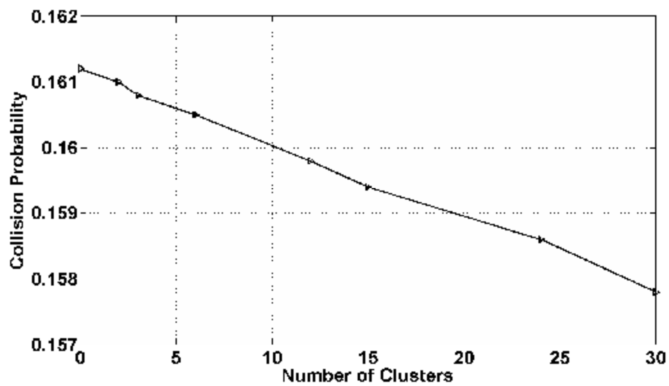

Figure 3: Collision probability vs. Number of clusters

In Figure 3, the curve shows how the collision probability is changing with respect to the number of nodes and clusters. When the number of nodes reduces and the number of cluster increases then the collision probability comes down.

5.2. Throughput

The throughput is calculated using equation (4). We have considered that β is set to maximize the throughput. The values of collision probability computed using (3) previously are used in the equation (4) to compute the throughput.

Table 1: Network Throughput for different numbers of clusters

Number of Nodes	Network Throughput (MBPS)	Number of clusters
20	1.9100	30
25	1.9084	24
40	1.9062	15
50	1.9067	12
100	1.9035	6
200	1.9033	3
300	1.9028	2
600	1.9025	0

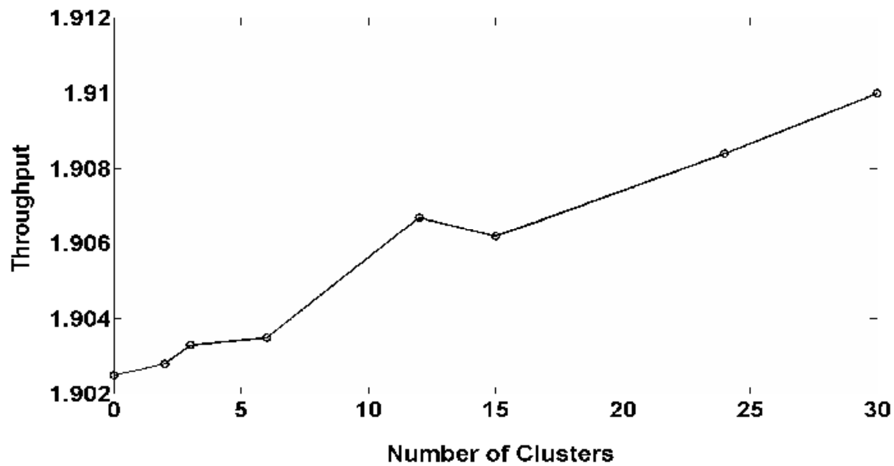

Figure 4:Throughput vs number of clusters

In Figure 4, the graph shows the throughput variation agaist the number of clusters. As the number of clusters increase the number of nodes reduces and this in turn increases the probability with which a node can complete a successful data transfer increases and this results in an increased throughput.

5.3. Backoff Period

The backoff period is calculated using eqn.(8). The values of collision probability computed using eqn.(3) are used in the equation (8) to compute the back off period.

Table2: Back off Periods for different numbers of clusters

Number of Nodes	Backoff Period (μ s)	Number of clusters
20	172.744	30
25	172.950	24
40	173.200	15
50	173.370	12
100	173.538	6
200	173.630	3
300	173.700	2
600	173.754	0

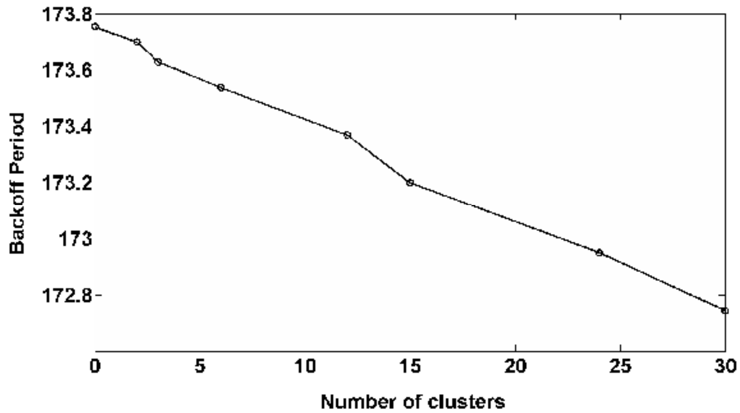

Figure 5: Backoff period vs number of clusters

In Figure 5, the graph shows that the backoff period of the colliding nodes is getting shorter as the number of nodes reduces. This is possible only when the number of clusters is increased.

5.4. Power Saving

The power reduction ratio is given by:

$$\frac{P_{tc}}{P_t} = \frac{1}{M^2}$$

As the number of clusters increase the power requirement in the clustered network is greatly reduced in comparison with the conventional network.

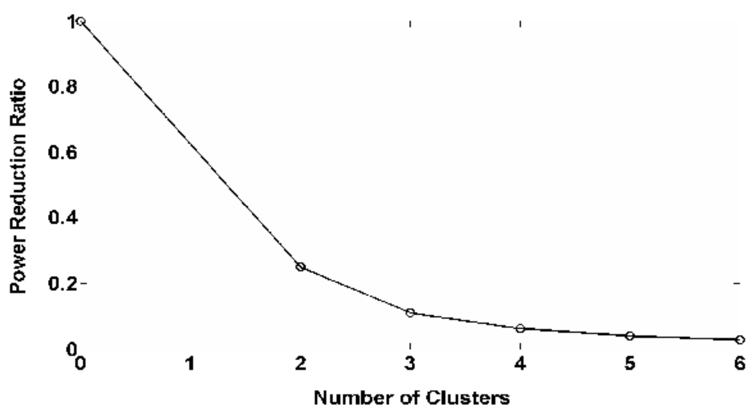

Figure 6: Power reduction ratio vs number of clusters in the axis of transmission

In Figure 6, from this graph it is evident that that power requirement of the network reduces drastically as the number of clusters increase. This is obvious because the secondary nodes which are more in number have a much lesser transmission range when compared with the conventional network. However the fact to be taken care of is increasing the number of clusters increases the number of primary nodes which dissipate more power. Hence the number of clusters must be appropriately chosen so that the reduced power requirement of our proposal holds true.

6. CONCLUSIONS

In this paper a mechanism has been proposed for an ad-hoc/sensor network in which they are broken up into clusters with each clusters consisting of two types of nodes. The node classification is on the basis of range variation. Each cluster has a primary node and many secondary nodes. The secondary nodes communicate among each other and use the primary node which has a larger transmission range to carry their inter-cluster traffic. The proposal being made increases the network throughput, reduce power consumption, improve reliability and increase the fairness of the system as well. These claims have been verified by the results obtained by taking help from the derived mathematical analysis. An important trade-off between the numbers of clusters versus effect of interference on throughput has also been discovered which can be a very important subject of study. This work can also be extended by making an analysis of throughput in ad-hoc/Sensor networks using MIMO technology and using efficient scheduling algorithms.

The paper is pursued to specifically identify problems existing in wireless Ad-hoc sensor networks and some solutions proposed to overcome such problems. However there are some limitations that have been identified in the project work. The results prove that when the network is spitted the benefits are enormous. The power consumption is reduced, the network throughput and the bandwidth available per user increases. But the splitting cannot continue indefinitely because these will lead to increase in the number of primary nodes.

With the increase in number of primary nodes, the power consumption of the network increases as they have a higher transmission range and also forward packets from other nodes. Too many primary nodes also increase the network overhead and this leads to the degradation of throughput efficiency. Intra-cluster network is adversely affected because they will be processing requests from nearby primary nodes to relay or receive packets. The secondary nodes in each cluster which rely on the primary nodes for communication with nodes in other clusters have longer delays for processing of their packets.

The above discussion points that the number of primary nodes in the network needs to be controlled. Investigation of the adequate number of nodes can be pursued in the future. The effects of introducing MIMO technology in the primary nodes can be pursued. When the nodes are equipped with MIMO then the primary nodes can be increased and they will be able to process more requests from the secondary nodes and at the same time take part in communicating with nodes from neighbouring primary nodes. The spatial reuse increases significantly which in turn increases throughput of the network as a whole. However in order to utilize these advantages an efficient antenna orientation algorithm needs to be proposed which will result in minimum collision among signals of various nodes.

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