MAXIMIZING THROUGHPUT WHILE MAINTAINING FAIRNESS AND PRIORITY IN WIRELESS AD-HOC NETWORKS

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ABSTRACT

Ad-Hoc wireless network, not a new field of research, has been gaining a lot of popularity in recent years because of its applications in emergency rescue, surveying, military, sensor networking, entertainment and community wireless networking etc. A lot of research has been done on improving the performance and capacity of ad-hoc networks in that period of time. However, not much has been done in the analytical modeling of inter nodal interference and its effect on transmission patterns of wireless ad-hoc network. In our work we investigated and developed a contention based ad-hoc network to study the interference impact on network performance. In our model we represented these inter nodal conflicts using 'Conflict Graph or Conflict Matrix' and presented scheduling schemes to address issues like network throughput, fairness and QoS (priority) in a network. We particularly studied the transmission patterns in a network given a specific conflict graph which in turn depends on factors like number of nodes and their placement, area of coverage, type of antenna (unidirectional or omnidirectional) etc. We designed five scheduling schemes in order to provide solutions to issues like maximizing network throughput, fairness and priority using the concept of 'Transmit Groups', which are groups of nodes that are capable of transmitting together without any interference.

For simulations, we have assumed a central entity which controls and schedules packet transmission from nodes. Using MATLAB simulations, we analyzed the throughput in hundreds of sample networks which differ based on number of nodes, number of conflicts and number of high priority nodes in the network. With the help of these results we not only proved that interference is an important factor in performance of wireless ad-hoc networks , but also its impact on different aspects of network depends on the number of nodes and number of conflicts. Based on the length of longest transmit group in a network and its variation with number of nodes, we calculated the maximum throughput possible. In our QoS schemes, we compared the success rate of achieving a pre assumed relative throughput by S-D pairs.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined the thesis titled "Maximizing Throughput While Maintaining Fairness and Priority in Wireless Ad-Hoc Networks" presented by Neelabh Krishna, Candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER-1

INTRODUCTION

In this chapter, we will discuss about the history of wireless ad-hoc networks, their basic structure, applications in modern world and also the scope of this work.

1.1 Purpose

Ad-Hoc: 1. Formed or used for specific or immediate problems or needs.

2. Fashioned from whatever is immediately available.

(Merriam-Webster Dictionary)

Ad-hoc networks work exactly same as the literal meaning of the word "Ad-Hoc". These networks are formed by a collection of independent wireless nodes, communicating with each other, without the support of any existing infrastructure. This concept of peer to peer communication is gaining a continuous popularity because of its various applications in the field of Military, Emergency Services, Commercial and civilian environments, Home and enterprise networking, Entertainment, Sensor networks and even in case of coverage extension for cellular networks or as last mile in small community networks. A lot of research has been done in some of the fields like military, where these flexible, dynamic and autonomous networks are being used for military communications and operations and even for the automation of battlefields. But some fields are quite new and open to a lot of research. For instance, use of these networks in emergency situations like earthquakes, tornados, hurricanes, floods and other natural disasters. In such cases these networks can be used in search and rescue operations, disaster recovery, policing and firefighting, supporting medical services etc. Since we don't have ease of well-established communication networks in such situation, ad-hoc networks provide solution where nodes can communicate without any assistance of a base station or any infrastructure.

Although wireless research community looked for huge opportunities in wireless ad-hoc networks only in the mid-90s, the basic concept of such networks is not so recent. These networks have roots in development of Packet Radio Network (PRNet) by DARPA in 1972. PRNet was designed to provide efficient means of sharing broadcast radio channel among many radios. Even though the first generation ad hoc networks became more useful with the addition of mobility, flexibility, independence from fixed infrastructure and smaller and powerful hardware it increased the complexity. These networks proved useful in military and defense applications. Creation of Mobile Ad-Hoc Network (MANET) working group of Internet Engineering Task Force (IETF) in 1997 made a way for ad-hoc networks in commercial wireless industry. The purpose of the this working group is to standardize IP routing protocol functionality suitable for wireless routing applications in both static and dynamic topologies with increased dynamics due to node motion or other factors. [1][2]

As ad-hoc networks advance, they become more and more complex which results in new technological challenges. One of the foremost of them is security of such networks. Since all nodes use a single shared radio medium in a potentially insecure environment, they are susceptible to denial of service (DoS) attacks that are harder to track down even in wired networks. [3] Apart from security, dynamic and mobile nature of wireless ad-hoc networks imposes a need for efficient routing protocol which can work in a multi-hop communication environment without causing excessive control traffic overhead or computational burden on the power constrained devices. [1] Self-sustainability property of ad-hoc networks without any infrastructure, poses a challenge for energy efficient systems. Communication related functions should be optimized to save unnecessary power. Satisfying Quality of Service (QoS) in wireless ad-hoc network is also a major problem because of unpredictable and rapidly changing RF characteristics. Due to lack of well-defined and widely accepted models for RF path attenuation, caused by refraction, reflection, scattering and multipath, mobility, traffic and interference among neighboring nodes finding a solution for above mentioned problems becomes challenging.

1.2 Medium Access in Wireless Ad-Hoc Networks

In any type of wireless network, interference from neighboring nodes is one of the major issues impacting the performance. This performance challenge has led to many researches in this field to find efficient MAC Protocols and Scheduling Schemes to minimize such conflicts. Since the wireless channel is inherently prone to errors and some unique problems such as the hidden terminal problem, the exposed terminal problem and signal fading, these MAC protocols become very important. Interference in a network varies with the variations in network size, coverage area, density and relative positions of nodes, traffic, transmitting power and type of antenna etc. As signal carrier to interference ratio (C/I) decreases, effective throughput of the network decreases, therefore for performance evaluation of wireless ad-hoc networks, it is important to have a good estimate of the interference levels.

Various MAC Protocols has been developed in past years to deal with this problem. These protocols can be broadly classified into two groups:

1. Contention Free MAC Protocols:

   In such schemes certain assignments of physical parameters are used to avoid conflicts. Four major protocols of this type are:

   a) Space Division Multiple Access (SDMA): In this type we divide space to get multiple access on the single channel. Use of directional antennas is one way to implement this technique.

   b) Time Division Multiple Access (TDMA): This scheme makes use of time slots. Each node can be assigned time slots during which it can use the medium and all others conflicting nodes must wait.

   c) Frequency Division Multiple Access (FDMA): In this type of multiple access, the full bandwidth is divided into channels or frequency bands which can be assigned to separate nodes for their exclusive use. This scheme has problem of Bandwidth limitation which should be handled.

   d) Code Division Multiple Access (CDMA): In this technique streams of data can be modulated using a node specific unique code and are fed into the channel. At the receiver, the data can be obtained by using the same code. Data from other nodes can be neglected as noise.

   Two or more of these can also be combined to enhance the performance of the network. We use TDMA to implement scheduling schemes in our work.

2. Contention Based MAC Protocols:

   The basic idea behind contention based protocols is the competition for the channel. These protocols cannot provide QoS, since channel access cannot be guaranteed beforehand. In such protocols usually throughput is comparatively low because of collisions especially in case of high traffic or higher number of conflicts in the network. Such protocols can be further classified on the basis of reservation and collision resolution mechanism they use to enhance the network performance.

Full classification of MAC protocols used for wireless ad-hoc networks is shown below in Fig. -1 [5].

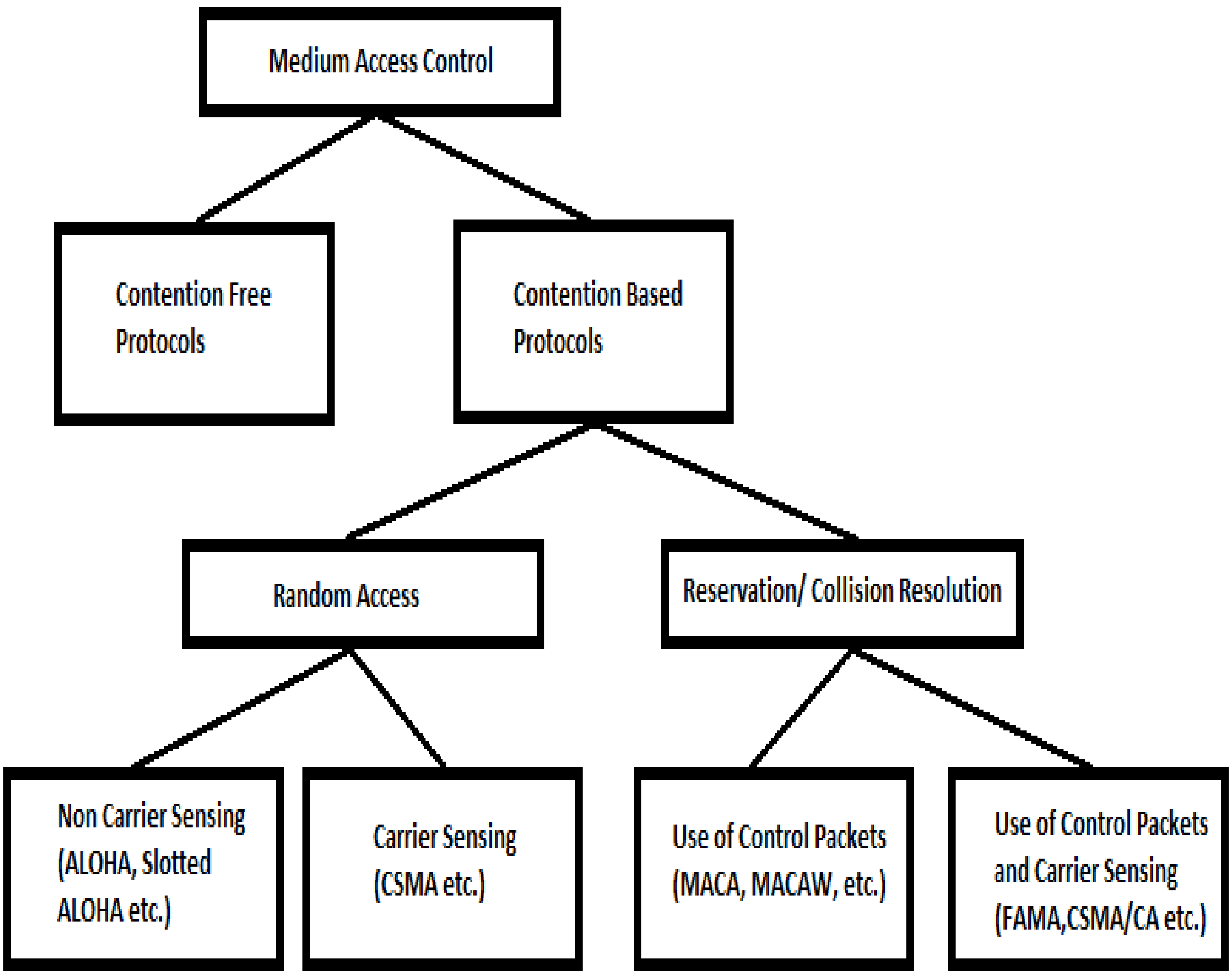

Fig.1.1 Classification of MAC Protocols used for Wireless Ad-Hoc Networks [5]

1.3 Scope and Outline

In this present work our focus is on maximizing the total network throughput, which is the sum of throughput of all individual source-destination pairs, satisfying other network conditions like fairness in throughput distribution among nodes or priority in scheduling for some users over others. In a contention based Ad-Hoc Network where all nodes have a range to communicate with all other nodes, only one of the entire set can transmit at one point of time. Therefore relative throughput (sum of the total number of times each node transmits / number of slots per frame) for that network will be 1.0. But with fewer conflicts, multiple simultaneous communication sessions can occur if they do not interfere with each other. Therefore throughput can be much greater than 1.0. So we can say that, in a practical network, all the network performance parameters depend on these simultaneous communication sessions or 'Transmit Groups' instead of individual nodes. We have studied the impact of these transmission patterns or Transmit Groups on network throughput for a number of networks varying in size, conflicts which in turn depend on factors like number of nodes and their placement, area of coverage, type of antenna (unidirectional or omnidirectional) etc.

A large number of transmit groups are possible in a single network depending on above stated factors. After investigating the pattern of these groups, we used some specific groups, in our scheduling schemes to get maximum network throughput, better fairness and to meet the requirements of high priority nodes. This selection is based on various conditions varying with the objective of the specific scheme. We then simulate theses scheduling schemes and analyze the results for different networks.

1.4 Organization of Thesis

The thesis is organized as follows. Chapter 2 provides a background of the concepts which we use in our network model and also incorporate the research done to analyze the impact of conflicts on the performance of wireless ad-hoc networks. Chapter 3 focuses on the scheduling schemes, which we have developed, for maximizing network throughput, providing fairness to throughput distribution and meet the requirements of high priority approach. Chapter 4 has description of the simulation model and its results. Chapter 5 puts forth the conclusion and also lays direction for future work in this field.

CHAPTER-2

BACKGROUND

This chapter gives a background of our work presented in this thesis. Here, we will discuss about the basic concepts which we used and the related research work in the field of wireless ad-hoc networks which have been done in the past few years.

2.1 Conflicts/Interference in Wireless Ad-Hoc Networks

Interference: A coherent emission having a relatively narrow spectral content, *e.g.,* a radio emission from another transmitter at approximately the same frequency, or having a harmonic frequency approximately the same as, another emission of interest to a given recipient, and which impedes the reception of the desired signal by the intended recipient. [13]

In wireless ad-hoc networks communication between nodes takes place over radio channels. As in most of the ad-hoc networks, all nodes use the same frequency band for communication which results in severe interference caused by neighboring nodes. Variations in network size (number of nodes), network density (relative positions of nodes) and traffic per node could have a strong influence on interference experienced by nodes throughout the network [4].

We use a "conflict matrix" to model the effects of inter nodal interference caused by neighboring nodes. Conflict matrix basically shows which source-destination pairs have mutual interference and hence cannot be active simultaneously. It is a two dimensional matrix having source-destinations pairs on both of its dimensions. If there is a conflict between two pairs i and j than (i,j) and (j,i) element of this matrix is 1 otherwise it's 0. It gives a basic idea of network configuration and network traffic workload in a network. As conflicts increase in a network (number of 1's in conflict matrix) different performance parameters behave differently.

Structure and definition of a conflict matrix will be clear by taking the case of below sample network (Fig 2.1). In this network we have considered 10 nodes (nodes 1 to 10) communicating with each other in 5 source-destination pairs (pairs P1 to P5). We have assumed that all nodes are equipped with directional antennas to minimize the conflicts among these pairs. We have approximated the shape of the main lobe regions as a wedge and side lobes and back lobe regions as a circle around the transmitting and receiving antenna [14]. The resulting shapes show the communication ranges for different pairs. So from the below network, it is clear that if a node belongs to one S-D pair present in the communication range of another pair then that former pair is interfering with latter pair. So here, pair P1 is in conflict with pair P2, pair P2 is in conflict with pair P1, P3 and P5, and so on. Such conflicts between the S-D pairs results in Conflict Matrix, Conflict Matrix for this example network is given in Table 2.1.

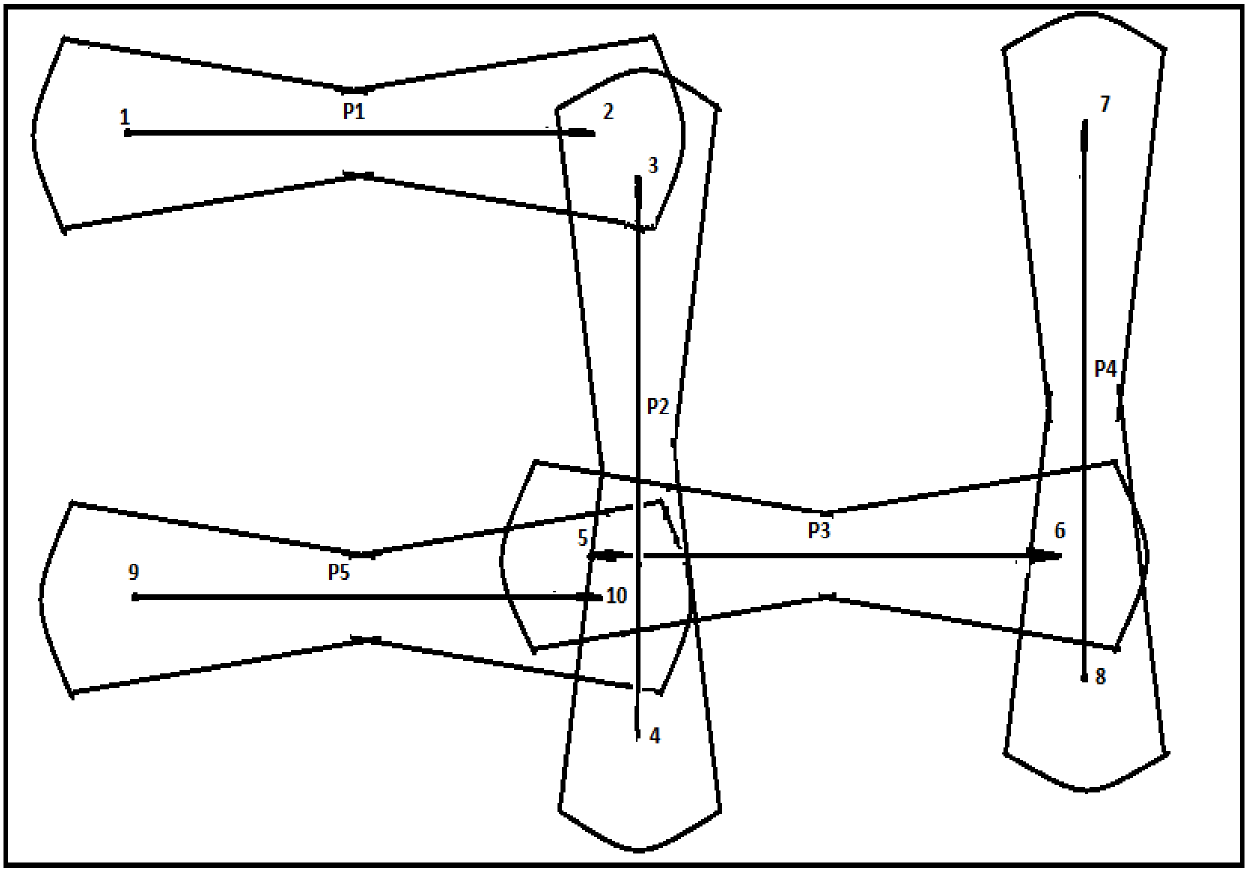

Fig 2.1 Sample Wireless Ad-Hoc Network using Directional Antenna

Table 2.1 Conflict Matrix for Sample Network

S-D Pairs	**1**	**2**	**3**	**4**	**5**
1	0	1	0	0	0
2	1	0	1	0	1
3	0	1	0	1	1
4	0	0	1	0	0
5	0	1	1	0	0

This Conflict Matrix gives an idea about how nodes will actually transmit or in other words, in which order S-D pairs can be activated depending on their conflicts with other pairs. For instance, P1 has only 1 conflict with P2, so P1 can communicate simultaneously with P3, P4 and P5. We called such groups formed due to inter pair interference as 'Transmit Groups'. In the next topic, we will discuss more about Transmit Groups and our approach to find them using graph theory.

2.2 Concept of Cliques in Graph Theory

In our approach, we have considered a wireless ad-hoc network as bi-directional conflict graph G= (V, E) where V is the set of vertices, which are the links between each source and destination nodes , and E is the set of links, which are the connecting edges formed by such pairs that are within the communication range of each other [7]. The conflict graph of the above sample network can be represented as shown in Fig 2.2. For this example we have Pi ϵ V and (Pi, Pj) ϵ E if links Pi and Pj have conflict with each other.

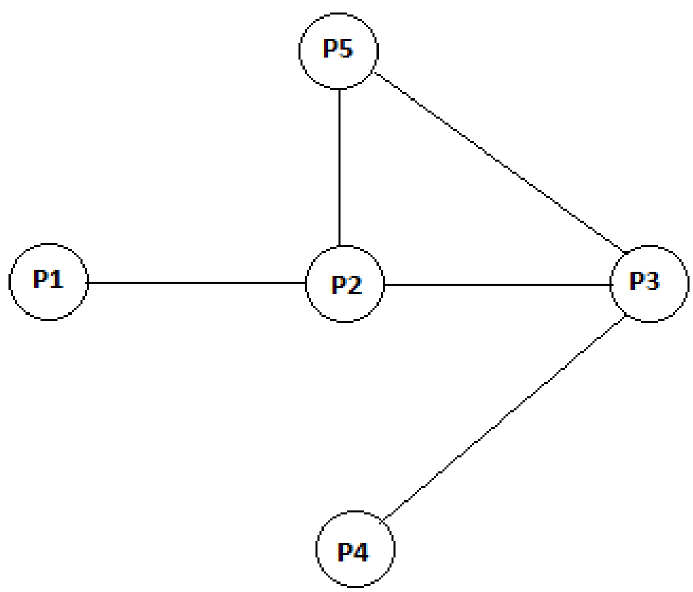

Fig 2.2 Conflict Graph for Sample Network in Fig 2.1

<u>Definitions</u>

1. Induced Subgraph: An induced subgraph is a subset of the nodes, in a bidirectional graph, together with any edges whose endpoints are both in the subset.
2. Complete Graph: A complete graph is a simple undirected graph in which every pair of distinct vertices is connected by a unique edge.
3. Clique: An induced subgraph that is a complete graph is called a clique.
4. Maximal Clique: A maximal clique of a graph is a clique that it is not contained in any other clique or in other words, a maximal clique is a clique that cannot be extended by including one more adjacent vertex, that is, a clique which does not exist exclusively within the vertex set of a larger clique.

As per the above definitions, a 'transmit group' can be represented by a maximal clique in our approach. Now to find all transmit groups in a conflict graph we have used Bron-Kerbosch Algorithm. It is an algorithm for finding maximal cliques in an undirected graph. The basic form of the Bron–Kerbosch algorithm is a recursive backtracking algorithm that searches for all maximal cliques in a given graph *G*. More generally, given three sets *R*, *P*, and *X*, it finds the maximal cliques that include all of the vertices in *R*, some of the vertices in *P*, and none of the vertices in *X*. Within the recursive calls to the algorithm, *P* and *X* are restricted to the vertices that form cliques when added to *R*, as these are the only vertices that can be used as part of the output or to prevent some clique from being reported as output. The recursion is initiated by setting *R* and *X* to be the empty set and *P* to be the vertex set of the graph. Within each recursive call, the algorithm considers the vertices in *P* in turn; if there are no such vertices, it either reports *R* as a maximal clique (if *X* is empty), or backtracks. For each vertex *v* chosen from *P*, it makes a recursive call in which *v* is added to *R* and in which *P* and *X* are restricted to neighbors of *v*, *N (v)*, which finds and reports all clique extensions of *R* that contain *v*. Then, it moves *v* from *P* to *X* and continues with the next vertex in *P*. The Bron–Kerbosch algorithm is not an output-sensitive algorithm: unlike some other algorithms for the clique problem, it does not run in polynomial time per maximal clique generated. However, it is efficient in a worst-case sense: any *n*-vertex graph has at most $3^{n/3}$ maximal cliques, and the worst-case running time of the Bron–Kerbosch algorithm is $O(3^{n/3})$, matching this bound [8]. From implementation point of view, we have used this algorithm in recursive manner. Every column of the returned matrix M corresponds to an independent set. If row i of column j is 1, then vertex i participates in the maximal independent set indexed by column j [18].

Now, we call set of all possible transmit groups in a conflict matrix as 'Transmitting Group Matrix', which is a matrix of size [Total number of transmit groups X Length of longest Transmit Group]. Transmitting Group Matrix for the conflict graph of Fig 2.2 is given below:

$$\text{Transmitting Group Matrix} = \begin{bmatrix} P1 & P3 & 0 \\ P1 & P4 & P5 \\ P2 & P4 & 0 \end{bmatrix}$$

Here each row represents one Transmit Group and 0s are used to fill the empty items in the matrix for groups smaller than the longest group.

2.3 Related Work

A lot of research has been done on the problems and challenges in wireless ad-hoc network because of the new emerging applications [1]. This research resulted in more efficient MAC and routing protocols, higher network capacity, better QoS, and more advanced hardware design for mobile ad-hoc nodes. But here we consider the work that is most closely related to our work.

There have been several systems and algorithms developed to meet the challenges of Medium Access Control in wireless ad-hoc networks. In such networks, MAC protocols are responsible for coordinating the access from nodes. In [5] and [9], the authors presented a comprehensive survey on MAC or Scheduling protocols, used in current wireless ad-hoc networks, integrating various related issues and challenges. They presented a classification of MAC protocols based on their operating principles and underlying features. In [10], impact of interference on such networks has been studied. Here, the authors used conflict graphs to model interference and presented methods for computing upper and lower bounds on the optimal throughput for given network and workload. In [7], the effect of interference on network capacity has been modeled by using 'clique' structures in the ad-hoc graph. The authors also proposed a fully distributed heuristic algorithm to approximate cliques in wireless ad-hoc networks. In [4], the authors proposed a model to calculate interference levels by taking into account the number of nodes, density of nodes, radio propagation aspects, multihop characteristics of the network and amount of relay traffic.

With advances in wireless ad-hoc technologies and growth of real-time and mission-critical applications, networks with QoS capabilities have been drawing a lot of interest. In [11] authors presented a scheme using two narrow band busy tone signals to ensure medium access for high priority to provide priority scheduling in wireless ad-hoc networks. In [12], the authors introduced improved bandwidth utilization into the model presented in [11]. Courtesy piggybacking scheme was used to explore the channel dynamics and to let high probability nodes help the low priority traffic by sharing unused residual bandwidth with courtesy.

In summary, there are a large number of papers published on MAC challenges and their solutions in ad-hoc networks. However, to our knowledge, a little has been done to analyze inter nodal interference and its effect on grouping of nodes that can transmit together in a wireless ad-hoc network. In our work we investigated and built a contention based ad-hoc network to study this impact of interference on network performance. In our model we represented these inter nodal conflicts using ‘Conflict Graph or Conflict Matrix’ and present scheduling schemes to address issues like network throughput, fairness and QoS (priority) in a network.

CHAPTER-3

SCHEDULING SCHEMES

In this chapter we will discuss our approach of centralized scheduling schemes to meet a set of performance requirements in wireless ad-hoc networks.

3.1 Scheduling in Wireless Ad-Hoc Networks

Current MAC protocols for wireless ad-hoc network provide channel access in 2 ways: contention based access and contention free access. The former, e.g. IEEE 802.11, consumes more energy due to collisions and idle listening. When directional antennas are used, these approaches are even more difficult due to exposed node and hidden node problems. So even though contention free protocols, e.g. TDMA, are more complex and use network bandwidth for control messages, they are more energy efficient, since nodes can enter inactive or low energy state until their allocated time slot. And also there is less wastage of energy due to collisions or retransmissions [16].

In our research, we have proposed separate scheduling schemes to achieve maximum network throughput, fairness in throughput distribution and priority in wireless ad-hoc networks. We have used TDMA as MAC protocol for our schemes. The main task in developing a TDMA scheme for an ad-hoc network is to allocate time slots according to the current topology of the network and the throughput requirement of nodes. In contention based networks S-D pairs always communicate in groups and these groups are formed as a result of above two factors. So in our schemes, we allocate time slots to these 'Transmit Groups' of S-D pairs rather than individual ones, and as result network throughput depends on the structure, length and number of transmit groups. We have used the concept of maximal cliques in an undirected graph to get these groups. To increase efficiency of the network, it is required to keep the number of transmit groups in the actual transmission as minimum as possible.

3.2 Network Model

We have considered a network comprising a central entity which controls and schedules packet transmission between fixed S-D pairs. All links are considered bidirectional. Topology of network, which includes relative positions of S-D pairs and resulting interference, has been represented by using ‘Conflict Matrix’ or ‘Conflict Graph’, as discussed in the previous chapter. This conflict matrix is used as input in all our scheduling schemes. We can get such matrix by using algorithms discussed in [14].

To measure the throughput in network we have used relative throughput which can be defined as follows:

$$\text{Relative Throughput per S} - \text{D pair}$$
$$= \frac{\text{Number of times S} - \text{D pair transmits in one frame}}{\text{Total number of Time Slots in one frame}}$$

$$\text{Total Network Relative Throughput}$$
$$= \frac{\text{Sum of the number of times all S} - \text{D pairs transmit in one frame}}{\text{Total number of Time Slots in one frame}}$$

So, in a network where each S-D pair has a conflict with all other pairs, total network relative throughput = 1.0. As number of conflicts decreases this value increases, for a network with absolutely no conflicts, it will be equal to the number of S-D pairs in the network. For example, if 5 S-D pairs have no conflicts, then they all can transmit in each time slot and network can achieve 500% total network relative throughput.

We have assumed each S-D pair is always greedy for channel access i.e. it always has information to send on the channel, in case of maximum throughput and fairness scheduling schemes. For priority schemes, we have assumed fixed values for required throughput by S-D pairs. These values have been selected in accordance with current technologies used in ad-hoc networks and their achievable network capacities.

3.3 Maximum Throughput

In a contention based wireless ad-hoc networks, throughput increases as contention decreases. Also the average length of transmit groups increases as number of conflicts decreases, because now more and more S-D pairs can access channel simultaneously. So, we can say that as the length of transmit groups increase, total network throughput increases. So maximum throughput for any network can be achieved by allocating all time slots in a frame to the longest transmit group. Our approach behind the scheme to attain the maximum throughput from a network is explained below:

1. As discussed earlier, input to our algorithm is 'Conflict Matrix' which depends on network topology. First step is to get all possible transmit groups for the above conflict matrix, which have been obtained by using Bron-Kerbosch Algorithm to find maximal cliques in an undirected graph.
2. Now, to achieve maximum throughput, we selected the longest transmit group (or transmit groups, if more than 1 group can have maximum number of S-D pairs).
3. The third step is allocating all time slots to above selected group (or groups in loop).

Relative throughput of the whole network can be calculated as follows:

$$\text{Relative Network Throughput} = \frac{\text{Length of longest transmit group} * \text{No. of time slots/frame}}{\text{No. of time slots/frame}}$$

= Length of longest transmit group

This is the maximum achievable network throughput in any wireless ad-hoc network for given topology. But a major drawback with this scheme is starvation of those S-D pairs which are not covered by the longest transmit group (or groups). Such pairs won't be able to get even a single time slot and hence their throughput would be 0.

3.3 Fairness in Throughput Distribution

Fairness is one of the most important considerations in performance analysis. But quantitative measures for fairness give different results from different perspective. Usually, any scheme resulting uneven throughput distribution among nodes is called Unfair. But an absolute fair scheme may badly affect the network throughput. For instance, in an absolute fair scheme, time slots will be equally distributed among all S-D pairs. Thus

$$\text{Relative Network Throughput} = \frac{\text{No of S} - \text{D pairs} \; * \text{No of time slots per frame/ No of S} - \text{D pairs}}{\text{No of time slots per frame}}$$

= 1.0

Here, network throughput decreases to its worst possible value. So, in our scheme we have divided network throughput among all the pairs in the fairest way possible while maintaining the total network throughput as high as possible. To measure fairness we have used Jain's fairness index [17] which can be given as:

$$\text{Fairness Index} = \frac{(\sum_{i=1}^{n} Xi)\ \hat{}2}{n * (\sum_{i=1}^{n} Xi\hat{}2)}$$

where n: number of S-D pairs in network

Xi= throughput of *ith* S-D pair

So, if all Xi are equal fairness index=1

Another idea behind to attain fairness in our scheme is that each S-D pair should allocate at least one time slot per frame to avoid starvation. Starvation in wireless ad-hoc networks can be defined in different perspectives. But in a broad sense it can be defined as throughput distribution in which a few dominating nodes receive very high throughput and many starving nodes receive very low (sometimes zero) throughput. Fairness scheme is explained below in detail.

1. In this scheme also, the first step is to attain all possible transmit groups from a given conflict matrix using Bron-Kerbosch algorithm.
2. Now, to maintain network throughput, we selected longest transmit group. If there are more than 1 transmit groups having the same number of pairs, then select one with the least number of conflicts among remaining S-D pairs (pairs which are not covered by that specific transmit group).
3. Now, as per our idea of fairness we had to cover rest of S-D pairs which is left out by first transmit group. For this we selected those transmit groups, which can cover these pairs in such way, so that number of time slots used to accommodate them should be minimum. This selection helps to improve the network throughput as nodes can transmit more times. Also, in case of any equality, select those transmit groups which have more number of node pairs to further increase network throughput.

4. Final step was allocation of time slots to above selected transmit groups in loop.

Relative Throughput per S-D pair can be calculated as:

$$\mathrm{Xi} = \frac{\text{No of times ith pair comes in selected TGs} * (\frac{\text{No of time slots per frame}}{\text{No of Selected TGs}})}{\text{No of time slots per frame}}$$

Therefore,

$$\mathrm{Xi} = \frac{\text{No of times ith pair comes in selected TGs}}{\text{No of Selected TGs}}$$

This throughput Xi can be used to get the fairness index for the network. The result ranges from 1/n (worst case) to 1 (best case), and it is maximum when all users receive the same allocation. Now to cover all S-D pairs, we had to allocate time slots to some shorter transmit groups which results in decrease of total network throughput. So as the fairness increases throughput decreases. But if all the pairs selected are of maximum length than network will be fair with maximum network throughput.

3.4 Priority Scheduling

With the growth of real time and mission critical applications, QoS becomes an important aspect of performance studies. Priority scheduling is one of the ways to achieve required QoS parameters. In priority scheduling some nodes get higher priority in resource allocation than the others [12]. We can take, emergency ad-hoc networks, as one of the practical examples of such requirements. Here, nodes used by emergency services, like security, medical, rescue etc., should get higher priority over others.

In our work, we have proposed 3 different schemes which can be used for different applications or for different requirements. They differ based on how they meet minimum requirements for both high and low priority users. Here, we have divided S-D pairs in two priority levels i.e. High Priority and Low Priority depending on the throughput requirement of the specific node pair. The third type of throughput requirement for third scheme is 'Minimum Required Throughput' which must be satisfied by all node pairs before any priority resource allocation to any nodes. Number of high priority S-D pairs, which a network can accommodate, depends on the topology of the network and selection of high priority pairs. So, the performance of these schemes also depends on the selection of high priority pairs, apart from interference. For instance, performance will be better in a network with all high priority pairs can communicate simultaneously or in other words all of them comes in one single transmit group than a network in which high priority pairs are distributed among different transmit groups. All 3 schemes are discussed below in detail.

3.4.1 Priority Scheduling Scheme-1

This scheme can be used in such situations where, high priority S-D pairs should get preference in resource allocation over the other. One of the examples is emergency ad-hoc networks in which emergency service nodes should get priority over others. Here, we have tried to meet the requirements of as many high priority S-D pairs as possible. Low priority S-D pairs which have a conflict with any of the high priority pairs would not communicate until the conflicting high priority pairs meet their requirements. The algorithm is discussed more in detail as below.

1. Here also, the first step is attain all possible transmit groups from a given conflict matrix using Bron-Kerbosch algorithm.
2. Now, we need to find the maximum number of high priority S-D pairs, which a network can accommodate based on their throughput requirements. For this, we calculated number of different transmit groups to which we can allocate time slots, so all High Priority pairs which are members of these selected groups meet their requirements. We can find out this number as

   N =floor (100/High Priority S-D pair Throughput Requirement)

   N is the number of different groups that can have high priority users and still meet throughput requirements.
3. Now, in this scheme our preference is to meet the requirements of high priority S-D pairs. So, we selected all such transmit groups which can cover all high priority S-D pairs and arrange them in decreasing order of number of high priority S-D pairs covered by these selected groups.
4. Here, we need to consider 2 cases for time slot allocation. Firstly, if the number of selected transmit groups in above step is greater than or equal to N, then allocate time slots to first N number of transmit group. But, if the number of selected transmit groups in above step are less than N, than time slots can also be allocated to such transmit groups, where there are no higher priority pairs.

One of the major issues with this approach is starvation of low priority nodes. As selection of transmit groups are primarily limited to only those which have high priority pairs, so it is not necessary that all S-D pairs can be covered by them.

3.4.2 Priority Scheduling Scheme-2

With this approach, High Priority S-D pairs only get extra throughput if and only if the conflicting low priority S-D pairs meet their throughput requirement. So in other words we can say that High Priority will come into picture only if there are some extra time slots available after satisfying all the Low Priority pairs. This approach will be useful in situations where high throughput requirement is not a necessity but implemented only to increase QoS for some users. One of the examples of such application is providing additional services like HD Video. So in this case, a user can stream HD video only when bandwidth is available and no other user wants to access the channel.

The algorithm for this scheme is discussed below:

1. The first step is attaining all possible transmit groups from a given conflict matrix using Bron-Kerbosch algorithm.
2. Here, selection of transmit groups for time slots allocation is done in the same as we have done in scheme for Fairness in throughput distribution to maintain the fairness among all S-D pairs including high priority pairs.
3. Now for this step, we need to check whether S-D pairs meet their throughput requirement or not. If any pair fulfills its requirement, it will be removed from the transmission list for the next slot. So that means next time slot can be allocated to a high priority pair which has a conflict with that low priority pair. Also after a high priority pair meets the low priority requirement, it will be assigned least preference until all conflicting low priority pairs achieve their target.

Although there is no starvation in this scenario, it is difficult to meet the requirements of high priority pairs especially in case of large networks. So this scheme is suitable for those applications in which preference to high priority pairs is not a necessity but only an additional service.

3.4.3 Priority Scheduling Scheme-3

This scheme is similar to the scheme-2, with the addition of the concept ‘Minimum Required Throughput’. This minimum required throughput must be satisfied by all conflicting S-D pairs before giving any preference to high priority pairs. The application of this scheme can be a network which provides many different applications and some of them need more throughput than other. For instance, if a network provides voice call (basic and HD Voice) and video call, so here a basic voice call needs minimum required throughput, video call needs high throughput and if we still have some time slots available we can upgrade the basic voice call to HD voice. So this approach tries to satisfy everybody’s minimum or basic needs before any up gradation of service.

Algorithm for this scheduling scheme is discussed below:

1. The first step is same as of the above schemes, in which, we attained all possible transmit groups for a given network.
2. As in this scheme, initially no preference is given to any S-D pair, same procedure for selecting transmit groups was applied as in fairness and Priority Scheme-2.
3. In this step, highest preference, in time slot allocation, was given to those S-D pairs which are below than the minimum requirement. The second preference was given to the high priority pairs i.e. now in this approach, a high priority pair has to wait until all conflicting low priority pairs meet the minimum requirement. Least preference

was given to low priority pairs which have already met the minimum throughput requirement.

This is the basic idea of our approach of centralized scheduling schemes to meet a set of performance requirements according to their application. We will discuss about simulation model and the results for these schemes in next chapters.

CHAPTER-4

SIMULATIONS AND RESULTS

In this chapter, we will describe our simulation model and assumptions made in that model. We will also analyze the simulation results for our scheduling schemes. We will calculate and compare relative throughput and fairness index for maximum throughput and fairness scheduling schemes. We will also check the success rate for proposed priority scheduling schemes. Also network behavior with different varying parameters like number of S-D pairs in network, the number of conflicts between them, the number of high priority nodes etc. and reasons behind it will be analyzed.

4.1 SIMULATION MODEL

We have made some assumptions in our model to simplify the simulations and to understand the concept of inter-nodal interference in wireless ad-hoc networks. Although, some of these assumptions make our model somewhat impractical for modern world applications, with simulation we show the change in network behavior with the change in network topology and how we can manipulate it to get the desired result.

4.1.1 Assumptions:

For simulations, we have assumed that all nodes in the wireless ad-hoc network are stationary. In today's world, mobility is one of the most important characteristic of wireless ad-hoc network, but there are many applications which still use stationary wireless networks or networks in which slow moving users are able to adjust to new conflict matrices. An emergency ad-hoc network can be considered as a practical example of such networks.

In our model, we have assumed a central entity which controls and schedule packet transmissions by nodes. Also in the simulated networks all nodes communicate with predefined peers. So we have considered S-D pairs instead of individual nodes in this whole discussion and these S-D pairs have conflict with each other during transmission. In other words, we have used TDMA algorithms which support only single-hop scheduling. So nodes are only one hop away from each other and central entity allocates time slots to theses S-D pairs depending on their throughput requirements or to satisfy some special network performance features like fairness etc.

We have already discussed in previous chapters, that in wireless ad-hoc network S-D pairs always communicate in transmit groups. So, in our algorithms a schedule can be defined as the pattern in which time slots have been allocated to one or more transmit groups, according to the topology and the requirement of the network. This schedule has been repeated, in the loop, for the whole scheduling frame. We have assumed that, numbers of time slots in scheduling frame are always greater than the number of time slots in a schedule.

The conflict matrix, which can be determined by the topology and structure of the network, was used as input for all our simulations. We have defined and initiated some variables which are physical parameters or calculated values like number of S-D pairs in network, the number of conflicts in a network (in percentage with respect to the maximum number of conflicts possible when each S-D pair has a conflict with all other pairs), etc.. Some variables are calculated values like Transmit Group matrix, Schedule matrix, Average number of S-D pairs per transmit group, throughput per S-D pair and total network throughput etc. Also we used some variables used as loop variables to simulate our schemes repeatedly for the whole scheduling frame or even for different networks.

4.1.2 Simulation Plan:

For simulations, we have considered several different cases of network conditions, varying on the basis of number nodes, number of conflicts and, for priority schemes, number of high priority nodes and their throughput requirements. Each of such case has been further simulated for 100 different random networks having identical conditions given above, but different conflict matrix. We average the statistics of these 100 networks to arrive at a value for each case.

We have assumed ranges for different variables to make our simulations as practical as possible.

- Number of nodes in network: 20 to 50 nodes. As discussed above we have considered S-D pairs. So actual range used in the simulation is 10 to 25 S-D pairs per network.
- The number of conflicts: 20% to 80% with respect to the maximum number of conflicts possible when each S-D pair has a conflict with all other pairs.
- Required Throughput by different priority S-D pairs: The priority requirement for High Priority, Low Priority and the minimum requirement (only for Priority Scheme – 3) are assumed as 40%, 25% and 8% respectively. If we consider total network capacity as 11Mbps, then these values can be converted into 4.4Mbps, 2.5 Mbps and 800Kbps respectively.
- Number of High Priority Nodes (or S-D pairs): The number of high priority nodes was assumed as 40 % of total number of nodes in network.

4.2 SIMULATION RESULTS

At the end of each time slot, a variable '*allowedcount*' keeps the count of number of times each S-D pair is allowed to access the medium. Once we get this throughput per S-D pair, we can find out the other performance parameters by using equations given in previous chapters. Results from all different scenarios for different scheduling schemes are analyzed below.

4.2.1 Maximum Throughput

As we have discussed earlier, for any network maximum throughput can only be achieved if there is no conflict between S-D pairs and hence all of them can transmit in each time slot simultaneously. But in a practical network, this maximum network throughput decreases as conflicts among S-D pairs increase.

Fig. 4.1 shows the variation of maximum throughput w.r.t. number of S-D pairs in the network and number of conflicts among them. As the number of S-D pairs increase, probability of being simultaneously transmitted also increases. As a result size of the longest transmit group and hence network throughput increases. But this increase in throughput also depends on the number of conflicts in the network. It is evident from the Fig 4.1 that throughput increases more rapidly in a network with 20% conflicts in comparison to networks with 50% or 80% conflicts (Slopes of the plots for networks with 20%, 50% and 80% conflicts are 31.2, 13.6 and 5.6 respectively).

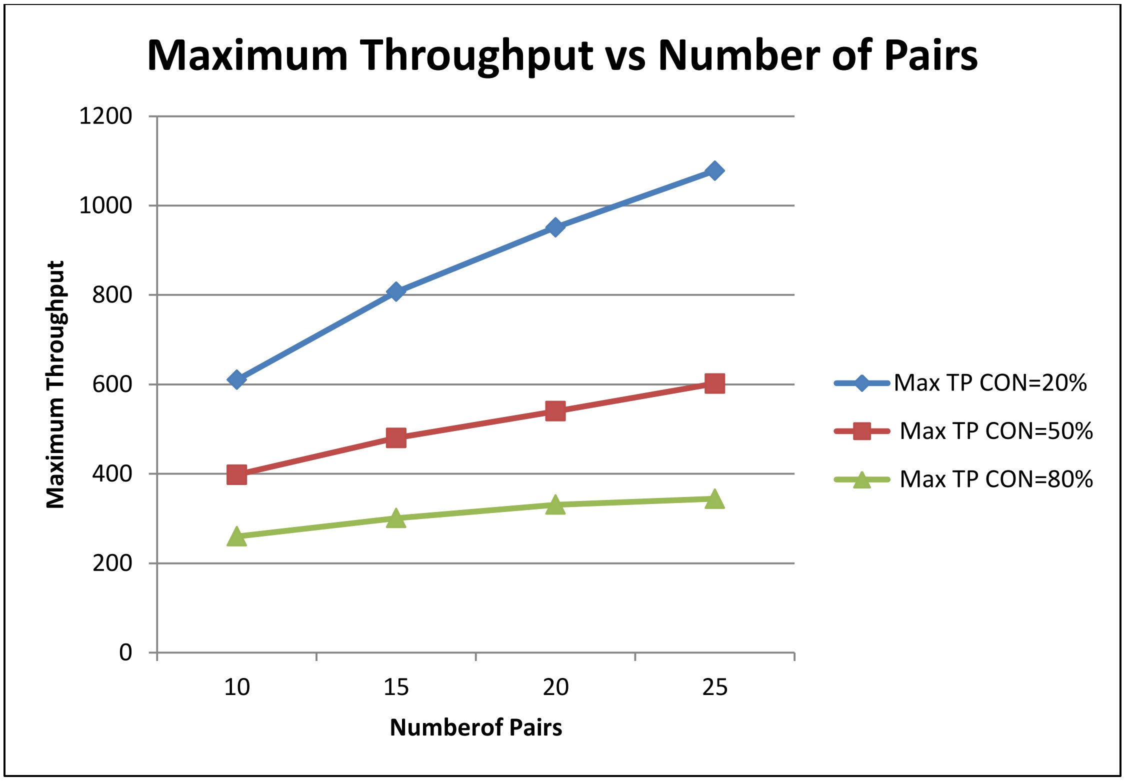

Fig. 4.1 Maximum Throughput vs Number of Pairs

4.2.2 Fairness

In ours fairness scheduling scheme, we assured that each S-D pair gets at least one time slot per frame. The basic idea was to avoid starvation in the network. So, in other words we have assumed that if there is no starvation in the network than the scheduling is fair. Now, performance of any scheduling scheme w.r.t fairness for any wireless network depends on number of transmit groups competing for channel, number of conflicts among S-D pairs which in turn decides the average length of transmit groups. In our scheme, these parameters affect the distribution of S-D pairs in the group of those selected TGs which are actually transmitted.

We can see from Fig. 4.2 that by keeping the number of conflicts the same, increase in the number of S-D pairs results in a decrease of fairness in throughput distribution. Also by comparing Fig 4.2 and Fig 4.3, we can deduce that this decrease in fairness with increase of the number of S-D pairs is directly proportional to the increase in the average number of pairs per transmit group for a specific number of conflicts. For example, from Fig 4.3 slopes of curves for 20% conflicts and 80% conflicts are 0.21 and 0.03 respectively, which are in direct proportion to the decrease in fairness in Fig 4.2 i.e. 0.2 and 0.08 for 20% conflicts and 80% conflicts respectively. So increase in number of pairs results in decrease in the factor

$$\frac{\text{Average number of S} - \text{D pairs per TG}}{\text{Total number S} - \text{D pairs}}$$

So in order, to cover all the S-D pairs, we have to allocate time slots to more and more Transmit Groups. This increase in the number of selected transmit groups made the distribution of S-D pairs less fair among them. Hence fairness decreases with an increase in the number of S-D pairs.

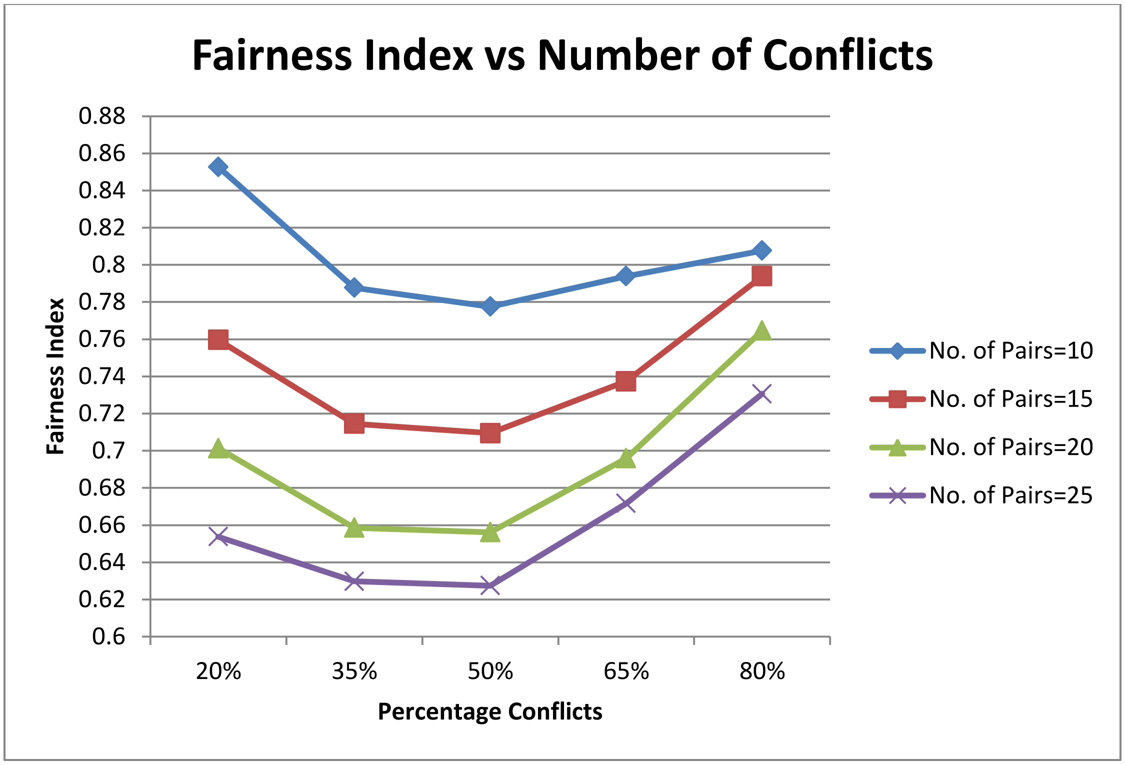

Fig. 4.2 Fairness Index vs Number of Conflicts

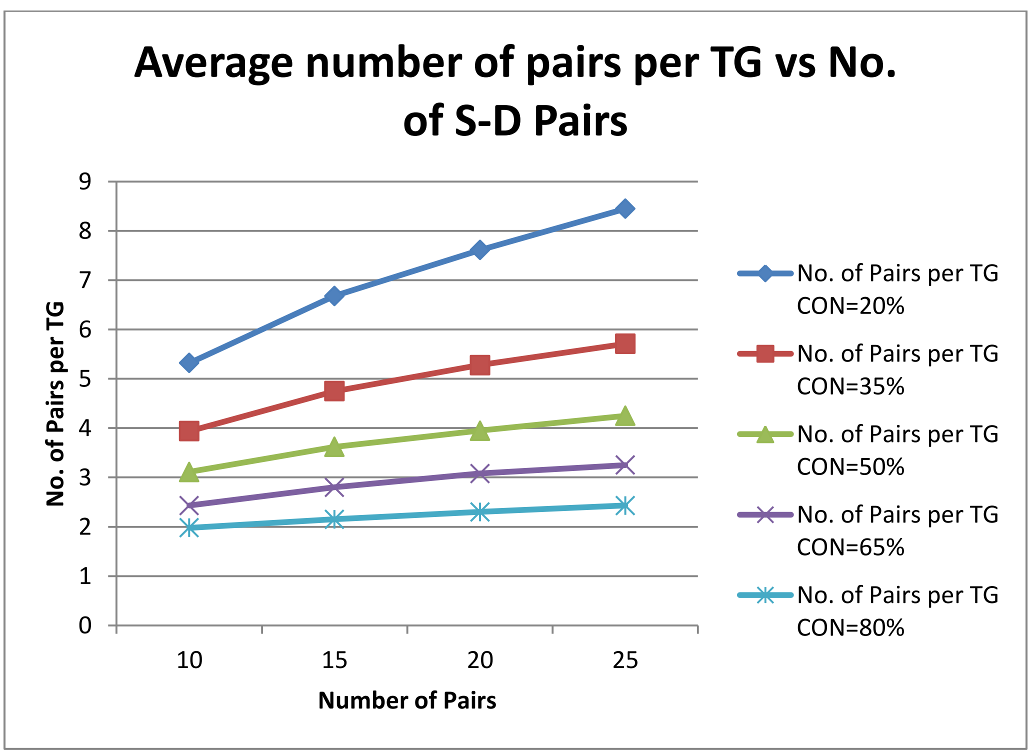

Fig. 4.3 Average Number of Pairs per Transmit Group vs No. of S-D Pairs

Now, again from Fig. 4.2 it is evident that the fairness is worst for networks with 50% conflicts and comparatively better for low and high number of conflicts i.e. 20% and 80% . For a network with a low number of conflicts, the number of S-D pairs per transmit group is quite large, so we need a less number of transmit groups to cover all pairs. So, S-D pair distribution in the transmit groups which actually transmit is fair and hence fairness in such networks is good. Fairness in such networks, with fewer conflicts, is highest when the numbers of nodes in the network are small. As the number of nodes increase, number of transmit groups in transmission increases and hence S-D pair distribution becomes less fair. For a network with high number of conflicts, average length of transmit groups is smaller which results in mutually exclusive transmit groups. So, in such networks, we have to select a lot of transmit groups for transmission but S-D pair distribution is fair. But for a network with an intermediate number of conflicts, all S-D pairs cannot be covered neither by a small number of transmit groups nor by mutual exclusive transmit groups. So in order to cover some specific pairs we need to allocate extra time slots to some other pairs. Hence such networks lack fairness in throughput distribution. We can take a hypothetical example of table 4.1 to make it clear. Here, we have taken networks with 4 S-D pairs and their probable transmit groups according to the number of conflicts in them.

Table 4.1 Example networks for fairness concept

No. of Conflicts (in %age)	Transmit Groups	Fairness Index
20	1,2,3,4	1.0
50	1,2 ; 1,3 ; 1,4	0.75
80	1,2 ; 3,4	1.0

4.2.3 Priority Schemes

In this section we have compared the results of our 3 priority schemes on the basis of two criteria i.e. number of high priority S-D pairs those meet their throughput requirements and total number of S-D pairs, including both low and high priority pairs those meet their respective throughput requirement. Number of high priority S-D pairs remains constant, which is 40% of total pairs, throughout the simulations.

Fig. 4.4 shows as the number of S-D pairs increase, performance for all 3 scheme declines. As in this figure we are just considering the performance of high priority pairs, schme-1 performed better than other two schemes. Scheme-2 and scheme-3 displayed the poor results because in those schemes initially there was no preference to any pair in those schemes and high priority pair received the extra throughput if and only if there were some time slots left in the time frame after fulfilling the throughput requirements of all conflicting low priority nodes. We have included the concept of minimum requirement (8%) in scheme-3, which is quite less than the low priority requirement (25%), so this scheme performed better than scheme-2.

Also, with the increase in number of conflicts in the network (Figures 4.4 (b) and 4.4(c)), performance of all three schemes decline. But it was interesting to note that rate of decrease for scheme-1 is much less than the other two schemes. This can be shown by comparing their performance for a network with 10 S-D pairs in fig 4.4 (a) and fig. 4.4 (c). Here, the difference between 2 networks is 26.75 % for scheme-1 in comparison of 92 % and 69 % for scheme-2 and scheme-3 respectively. So we can say that scheme-1 is best fit for networks where high priority nodes should get their required throughput for their normal functioning.

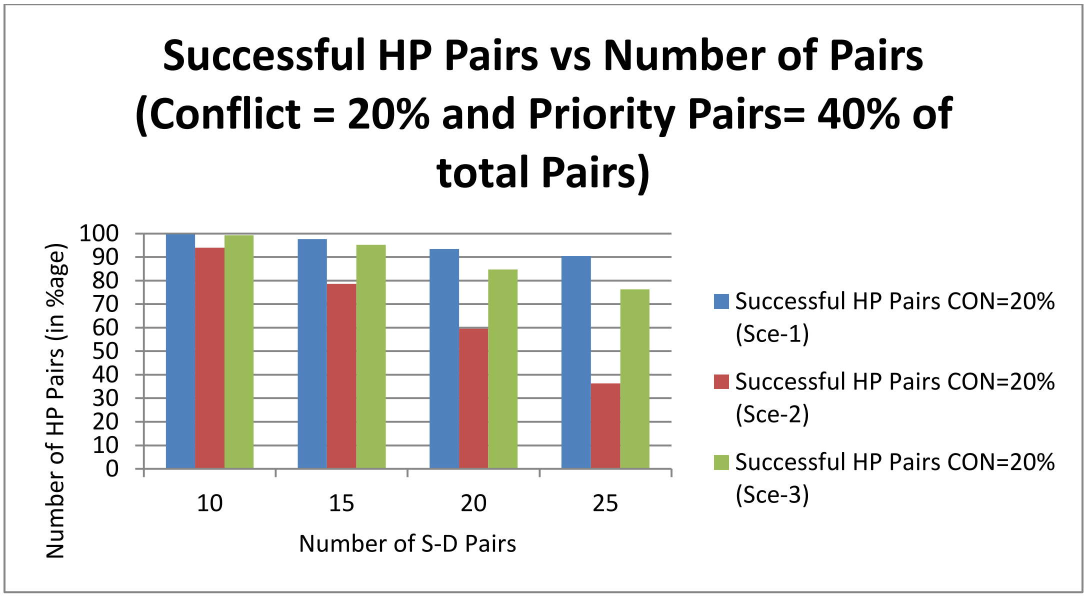

Fig. 4.4(a) Successful High Priority S-D Pairs vs Total No. of S-D Pairs (Conflict=20%)

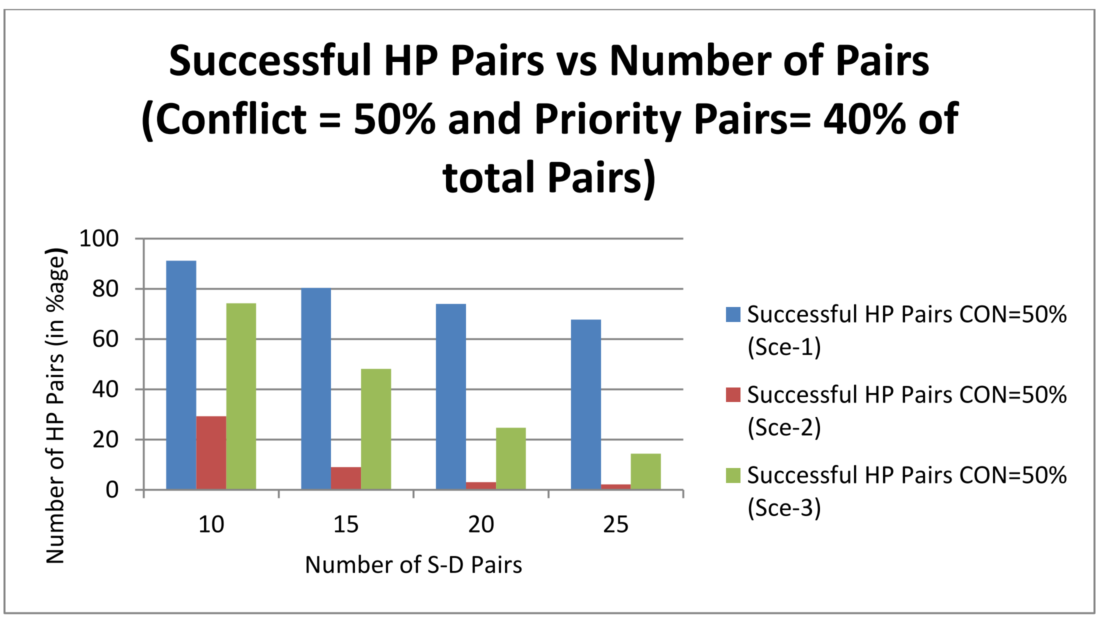

Fig. 4.4(b) Successful High Priority S-D Pairs vs Total No. of S-D Pairs (Conflict=50%)

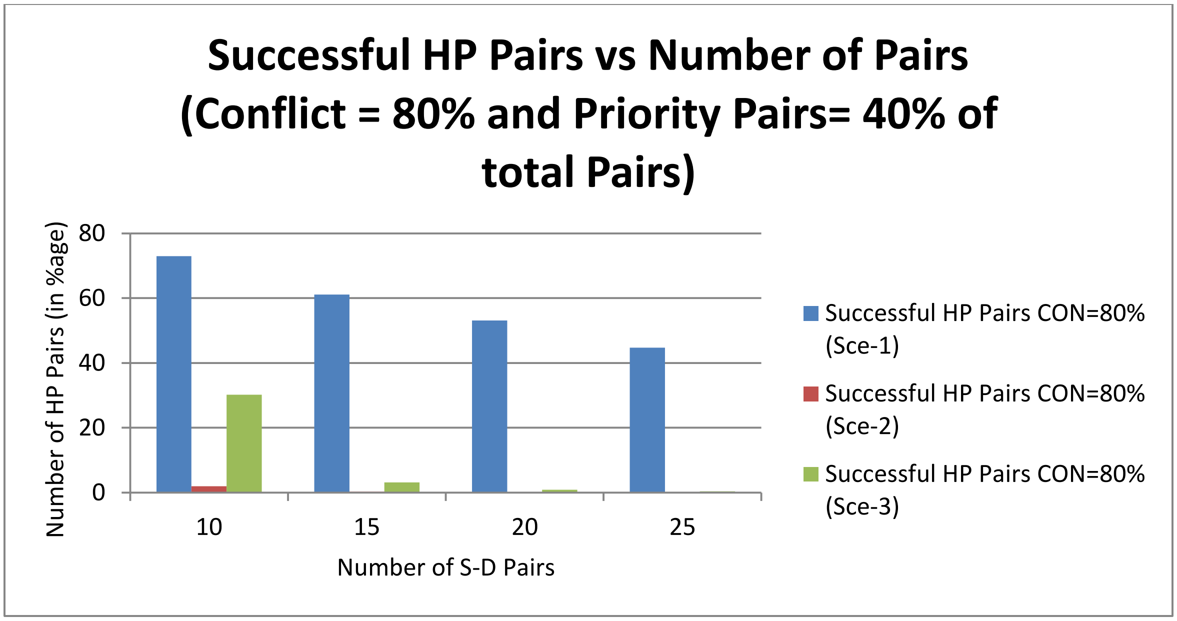

Fig. 4.4(c) Successful High Priority S-D Pairs vs Total No. of S-D Pairs (Conflict=80%)

Fig. 4.5 compares the results from 3 schemes for total number of successful S-D pairs, including both low and high priority pairs. We can use these results for networks where extra throughput to high priority nodes is required only to increase QoS but not necessary for their normal functioning.

For networks with fewer conflicts and less number of pairs, scheme-2 performed slightly better than the other two schemes (Fig 4.5 (a) for networks with 10, 15 and 20 S-D pairs). In scheme-2 as there is no preference for high priority S-D pairs, time slots are allocated to fulfill the requirement of low priority pairs which are, according to our simulation model, 60 % of the total number of S-D pairs in the network. As absolute numbers of low priority pairs are quite less, it would be easy to meet the throughput requirement of all such pairs and hence percentage of total successful pairs increases. But as number of S-D pairs or number of conflicts in the network increases, it would become difficult to fulfill the throughput requirement of 60% of S-D pairs (low priority) in comparison with the rest 40 % pairs (high priority). So for networks with more number of conflicts or more number of S-D pairs, scheme-1 had a better performance than other two schemes, which is evident from fig. 4.5(a) to fig. 4.5(c).

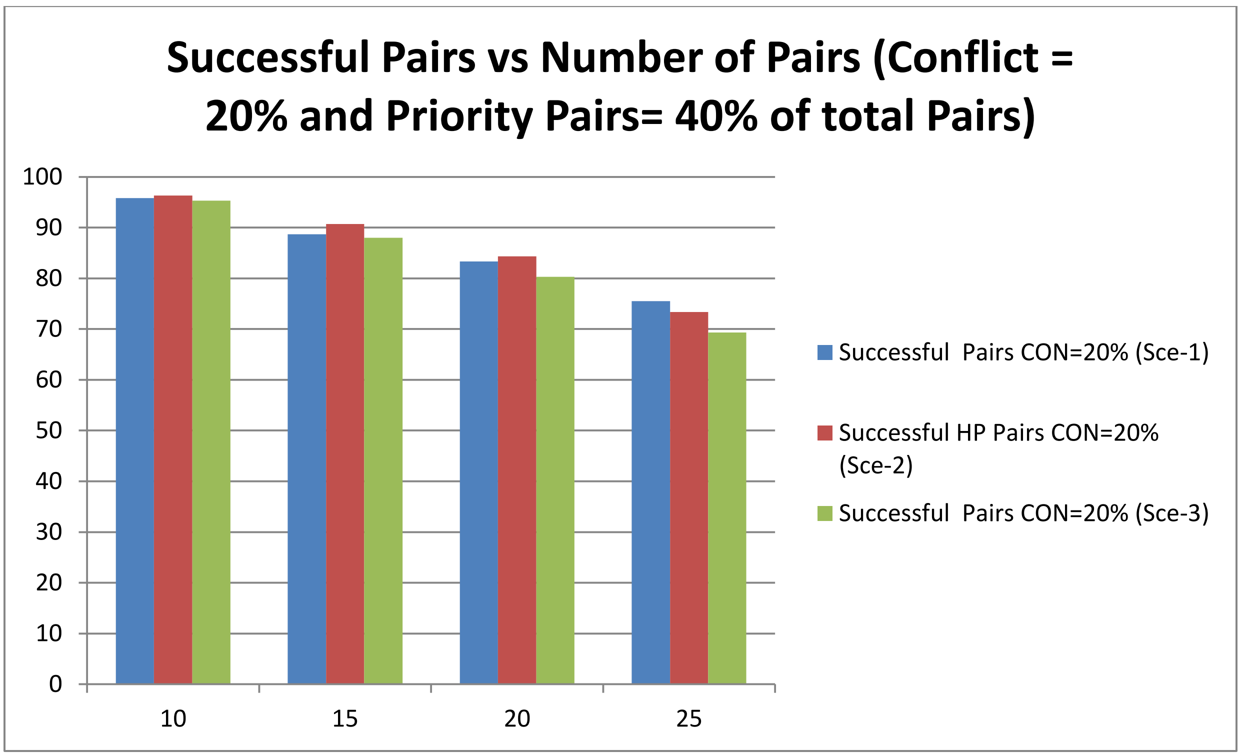

Fig. 4.5(a) Total Successful S-D Pairs vs Total No. of S-D Pairs (Conflict=20%)

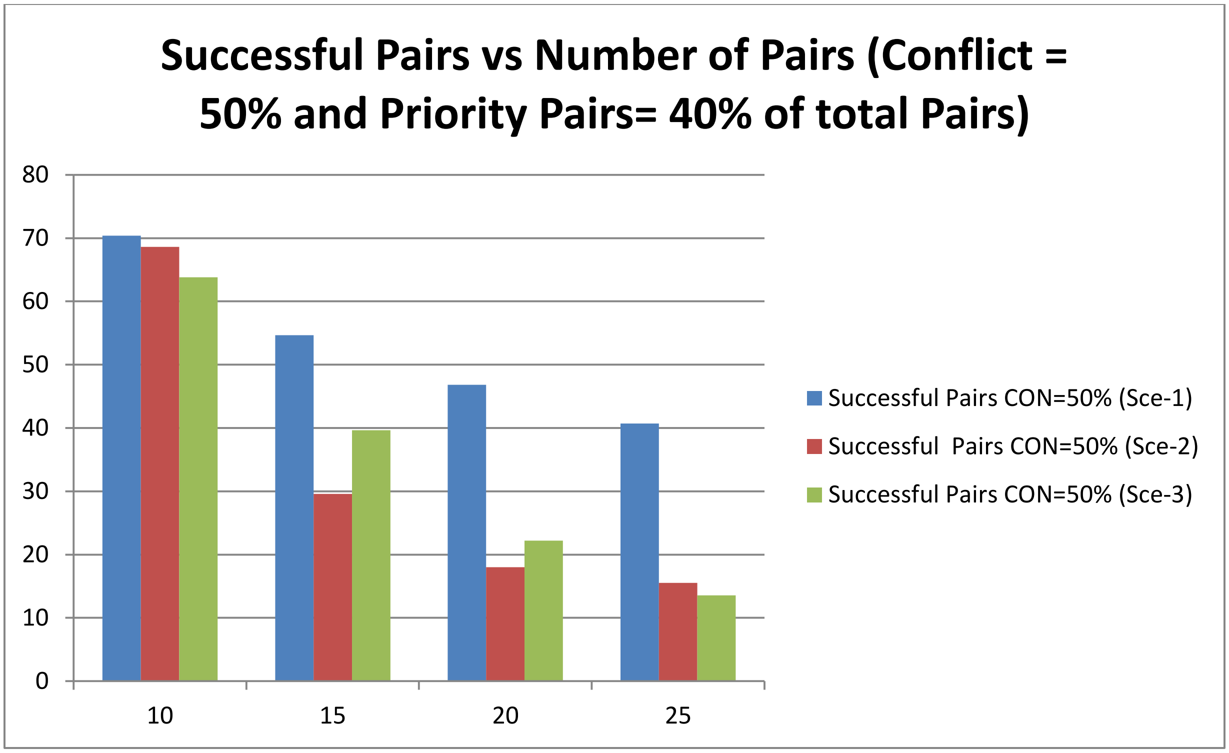

Fig. 4.5(b) Total Successful S-D Pairs vs Total No. of S-D Pairs (Conflict=50%)

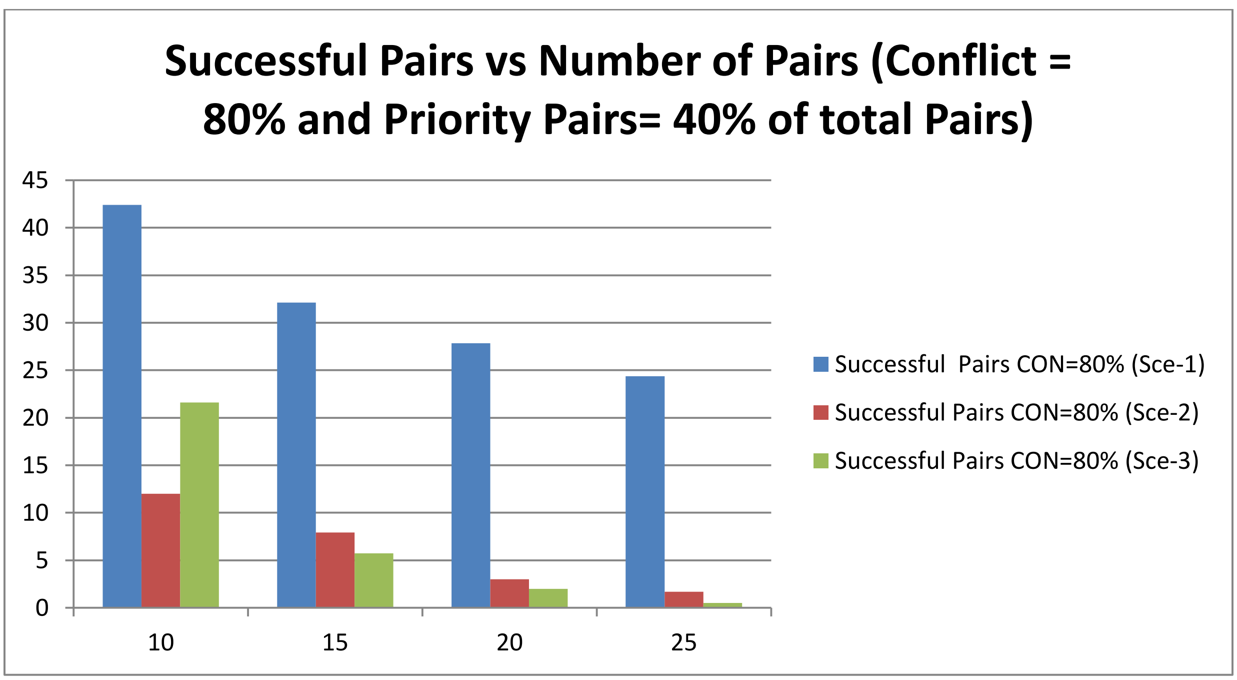

Fig. 4.5(c) Total Successful S-D Pairs vs Total No. of S-D Pairs (Conflict=80%)

CHAPTER-6

CONCLUSIONS AND FUTURE WORK

In this work we have studied the impact of inter nodal conflicts on capacity and fairness in wireless ad-hoc networks. We used a conflict matrix as our input to all simulations under various conditions (number of nodes, number of conflicts in network etc.) Based on the conflict matrix we presented the concept of transmit groups i.e. the groups of S-D pairs which can access the wireless channel simultaneously. Based on the results from the simulations we have concluded that throughput and fairness are dependent on these transmit groups rather than individual nodes. Maximum possible network throughput is dependent on the length of longest transmit group and fairness depends on the S-D pair distribution among transmit groups. We have also presented scheduling schemes to implement priority in wireless ad-hoc networks, according to throughput and QoS requirements. In these schemes we again use the concept of transmit groups. We manipulated these transmit groups by allocating the time slots to some specific groups in a specific order to get the desired results.

As for the future work, though all schemes have given satisfactory results, these can be improved to provide better and more practical solutions. In our work we have assumed a central entity which controls all communications between nodes but a decentralized way of communication will be more practical in nature. If all nodes known of the conflict matrix and use a common scheduling scheme than processing time can be reduced significantly. In today’s ad-hoc networks, nodes can be very dynamic and mobile like fast moving vehicles on a freeway in intelligent transit system, so implementation of mobility in these schemes will open a lot of other areas. Multihop communication is an important part of modern wireless networks, but it has not been taken into consideration for modeling in this study, so modeling multihop links would also be an essential part for a complete system solution.

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VITA

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