Channel Assignment for Inter-cluster links in Multi-Radio Multi-Channel Wireless Mesh Networks

By

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APPROVAL

It is certified that the contents and form of thesis entitled "*Channel Assignment for Inter-cluster links in Multi-Radio Multi-Channel Wireless Mesh Networks*" submitted by Muhammad Kashif has been found satisfactory for the requirement of the degree.

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IN THE NAME OF ALMIGHTY ALLAH

THE MOST BENEFICENT AND THE MOST MERCIFUL

TO MY PARENTS

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Muhammad Kashif

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Abstract

In Multi-radio multi-channel wireless mesh network architecture, a proper channel assignment scheme must reduce interference to a minimum level while achieving maximum spectral efficiency by means of channel reuse. Among other proposed schemes the Cluster-Based Channel Assignment Scheme (CCAS) significantly improves the overall network performance. CCAS logically partitions the network into non-overlapping clusters, while assigning a common channel to all nodes within the cluster and using orthogonal channels for neighboring clusters to prioritize the minimization of non-coordinated interference. Although CCAS significantly reduces the complexity of minimizing non-coordinated interference, but a significant attention has not been paid on channel assignment for inter-cluster links.

In our work we are enhancing this cluster based channel assignment by analyzing all aspects of non-coordinated interference (i.e. FH, NH and IA) among inter-cluster gateway nodes, thus maximizing the end-to-end throughput. Our analysis shows that for a given link, the interfering FH and IA directional links are always reverse of each other. This leads us to an idea that elimination of one type can automatically eliminate the other. In this way, while assigning channel for a link, we have to focus only on two types of non-coordinated interfering links. We have also computed the %age of interfering links for inter-cluster links and the possible interfering area where the nodes reside creating that interfering links. We have then proposed an inter-cluster channel assignment scheme on top of CCAS by utilizing 4 additional orthogonal channels. The proposed scheme exploits the trade-off between numbers of inter-cluster links and introduced non-coordinated interference. A sub-set of inter-cluster links is assigned orthogonal channels while remaining inter-cluster links are not assigned any channel. The scheme results in replacing certain inter-cluster links with the set of links have path length of up to 3. Simulation results show an improvement of 40% for single flows on inter-cluster links. Results also show up to 12% improvement in overall throughput for end-to-end flows.

Chapter 1

Introduction

Like the evolution of various wireless networks to enhance network performance and to offer better services, Wireless mesh networking (WMN) has also emerged as a key technology. Mesh connectivity considerably boosts network performance such as load balancing, throughput, fault tolerance and protocol efficiency. It offers low-cost, reliable broadband wireless network access. The reader can go through a detail survey on VMN at [1].

1.1 Multi-Radio Multi-Channel WMN

In WMNs, nodes are the collection of mesh clients and mesh routers as shown in Fig 1.1. Every node jointly acts as a host and as a router. The role of routers is as similar to access points in a traditional wireless LAN to provide connectivity to mobile clients, but they also have additional routing functions to support mesh networking, like they communicate wirelessly with each other over multiple hops and some of these access routers are wired and serve as internet gateways for the rest of the wireless network. The clients in the mesh network also have the arrangements for mesh networking, and can also act as a router. However, they do not have the gateway or bridge functions. As compared to mesh routers the mesh clients usually have only have one wireless interface, while the routers are equipped with more than one interfaces and using multiple channels for communication in mesh network. This type of mesh network is known as Multi-Radio Multi-Channel (MR-MC) WMNs.

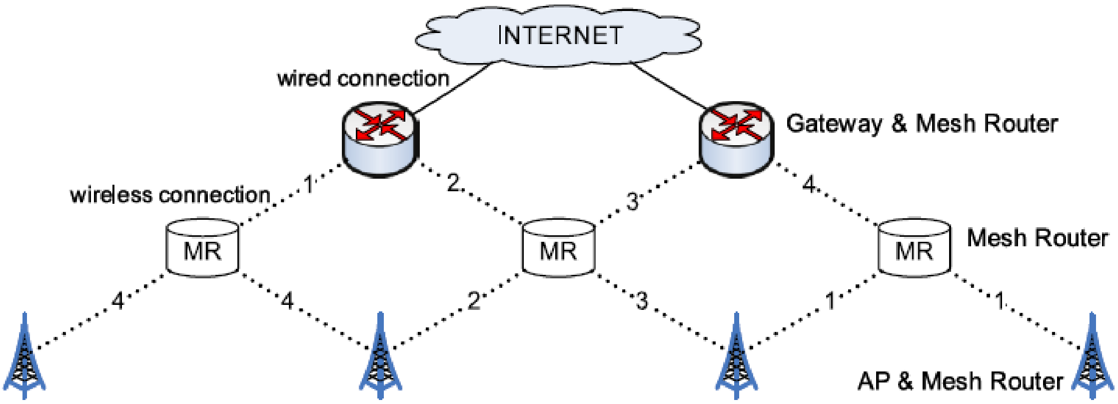


Fig 1.1: MR-MC Architecture in WMN [1]

Research has shown that usage of multiple channels in multi-hop wireless mesh networks considerably enhance the overall network throughput [2][3] and further enhances the flexibility of mesh networking. With each mesh router having multiple radios, multiple transmissions and receptions are possible at the same time, hence multiply the throughput. Today, the usage of online voice and video applications and Internet surfing is raising rapidly. Quality of service (QoS) is the most important requirement for these applications. To support high traffic load we generally add more bandwidth by setting up additional channels.

1.2 Channel Assignment in WMN

In Multi-Radio Multi-Channel (MR-MC) WMNs, Channel Assignment (CA) is the scheme or a strategy of assigning channels to the available radio interfaces on the routers in a mesh network. MRMC WMNs are commonly based on commodity 802.11 [4] hardware. In 802.11 radio spectrum the number of orthogonal channels are very limited i.e. 12 in IEEE 802.11a/g and 3 in IEEE 802.11b [5][6]. Due to limited availability of orthogonal channels, its essential to keep on improving the CA algorithms, so that better throughput and enhancement in network capacity can be obtained from better utilization of multiple radios and channels in WMNs.

MRMC WMNs advantages cannot be realized entirely unless the related issues i.e. channel assignment, link scheduling, node deployment and routing are not handled properly. Among all of the above mentioned the channel assignment (CA) issue has received extensive attention. This issue has taken the importance due to the reasons like, a problem that must be solved for the operation of MRMC WMNs and also challenging one as many of the proposed formulations of have turned out to be NP-hard.

1.3 Interference in WMN

An important design goal while improvising CA algorithm is to maximize the network capacity and the major challenge that severely affect the network capacity is **Wireless interference.** Wireless mesh networks are susceptible to interference that can cause a link to degrade substantially or fail altogether unlike wired networks where the affect of co-located links have no concern with the throughput of a link.

Garetto et al. [7] have presented an interference model and classify it to better understand the issues involved in the degradation of overall network performance. We have discussed it in detail in 2.2.1. On the basis of this classification of interference, Naveed [8] presented a cluster based channel assignment scheme (CCAS) in which non-coordinated interference (a type of interference) is attempted to minimize by using clustering approach. Localized channels are assigned for intra-cluster communication.

1.4 Problem Identification

Although interference minimization is the backbone strategy in channel assignment approaches to obtain optimal end-to-end through-put in MRMC WMNs, but another key tactic is to consider the links differently while assigning channels, due to the fact that different links have diverse through-put impact in MRMC WMNs. For example, the connecting links carry much more network traffic than the stub links, so more bandwidth should be allocated to that connecting links either by assigning less interfered channels or by assigning more number of parallel channels. Also in a typical WMN there may be several multi-hop flows spanning across multiple clusters, so just partitioning the WMN into disconnected clusters is not enough. Hence, in CCAS, it is necessary to establish a strong inter-cluster connectivity. While CCAS significantly reduces the complexity of minimizing non-coordinated interference, but a considerable attention has not been paid on channel assignment for inter-cluster links.

1.5 Research Statement

To analyze and minimize the non-coordinated interference among inter-cluster links in cluster based channel assignment scheme. This objective is to establish a strong inter-cluster communication among gateway nodes, thus maximizing the overall network performance.

1.6 Contributions

- Separate analysis of all modes of non-coordinated interfering inter-cluster links i.e. Far-Hidden (FH), Near-Hidden (NH) and Information-Asymmetric (IA).

- Detection of interfering links and mentioning of nodes that is either sender or receiver of that interfering links.
- For a given link, the interfering FH and IA directional links are always reverse of each other.
- Development of Inter-cluster links channel assignment algorithm.

1.7 Thesis Organization

The thesis is organized as follows:

Chapter 2 evaluates the related literature of channel assignment with the goal to minimize the interference in WMN. Existing body of work is broadly categorized and deficiencies are highlighted.

In Chapter 3, we discussed briefly the analysis performed for the non-coordinated interference. We highlighted the observations for all types of non-coordinated interference and explain that how we can avoid interference to obtain optimal throughput for a given WMN topology.

In Chapter 4, we proposed a channel assignment scheme and implemented that in OPNET for single flows and end-to-end flows. We compared it to network topology with random channel assignment and find out the impact on aggregate end to end throughput of WMN.

Chapter 5 concludes our thesis and describes the future work to be carried out in this domain.

Chapter 02

Literature Review

The following chapter provides a comprehensive overview of different methods for channel assignment in WMN. We have briefly discussed the literature review which we have carried out to find out the research gap in this crucial problem of channel assignment in WMN. In later part the interference model presented by Garetto et al [7] has been discussed in detail so that the reader can better understand the scope of interference on the communicating links and its major effect on the overall performance of a network

2.1 Channel Assignment Schemes

Channel assignment problem in WMN has draw extensive attention from both industrial and academic researchers. Hence there exist a lot of strategies proposed in the literature for channel assignment in WMN. The channel assignment problem has been proven to be NP-hard in [3]. Different ways are proposed for channel assignment like the dynamic switching of channels is proposed in Bahl et al. [9]. The idea is to periodically unite the neighbors on a common channel to communicate; the advantage in this way is that it neither requires multiple network interfaces nor the modification of the MAC protocol. The main drawback of this approach is to achieve nodes synchronization. Another tactic of channel assignment in Wu et al. [10] is by dividing the overall bandwidth in two different channel categories, one category having only one channel is fixed for the control information and the other category having remaining n channels is to transmit data packets. Another channel assignment approach designed by So et al. [11] in which the nodes having packets that are ready to transmit, first negotiate a specific time window with the destination than transmit the data in that window. This assumption taken in this approach is the synchronization of nodes prior to transmit packets in specified time window. A category of channel assignment approaches, which assumes that there are more than one interfaces per node. In this way Shin et al. [12] propose to assign multiple channels to a node for multiple interfaces as many as possible, so that overall network performance can be improved while satisfying the constraints of limited available channels and interfaces per node. On a particular network interface the channel selection is done randomly. A distributed channel assignment was proposed in Raniwala et al. [13]. In this scheme a WMN is represented as a multiple spanning trees with an assumption that a node can join multiple spanning trees and the network load is distributed among all the trees. The major drawback for this approach is that the proposed WMN tree connected the Internet is connected on the top; hence in the tree hierarchy the nodes positioned higher get a higher priority. The nodes positioned in the lower portion of the tree hierarchy will get lower priority while choosing channels. This process may result in discrimination among the nodes and their communication performance is affected negatively. Another distributed channel assignment algorithm proposed by Ko et al. [14] where the channel is chosen greedily by each node. In this way based on the local information a local objective function minimizes. The sum of the cost of interference within its range is calculated prior choosing the channel and based upon this calculation every node can select that particular channel that minimizes the interference cost. Although in this proposed scheme the process of assigning channels is only based upon the local information among nodes, but multiple radios per node are not considered in this scheme.

2.2 Interference in MR-MC WMNs

To address the interference issue, a model needs to be assumed describing the interference effect. Two widely-adopted models are used currently i.e. Protocol Model and Physical Model. Both of them are initially proposed in [15]. The Protocol Model illustrated as: a transmission from radio A to radio B is successful if B is in the transmission range of A and not in the interference range of radios other than A that are currently transmitting, each radio has a transmission range and an interference range, with the former less than the latter. A quite complex Physical Model but close to reality can be described as: the interference and noise power at the receiver consists of the noises generated by other ongoing transmissions and the ambient noise in the network, a transmission is successful if the Signal to Interference and Noise Ratio (SINR) of the transmitter's signal at the receiver is larger than a threshold value,.

It’s a well-known fact that interference can make a significant impact on the overall performance of a wireless mesh network. Gupta and Kumar has done a pioneering work in [16] and showed that in a wireless network by assuming random node placement and communication pattern with *n* identical nodes, the per-node throughput is È(1/*vn* log *n*). Under the assumption of optimal node placement and communication pattern it becomes È(1/*vn*). The authors in [15], by using a conflict graph have modeled the influence of interference and derive lower and upper bounds on the optimal throughput.

2.2.1 Interference Model

Garetto et al. [7] have broadly classified the interfering links as coordinated and non-coordinated;

Coordinated Interference: For a directional link l(i, j) – i being transmitter and j is the receiver – the directional link l’(i, j') is a coordinated interfering link if the Euclidean distance d(i, i') is less than the carrier sensing range (RCS).

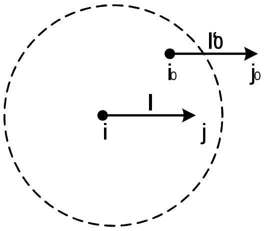


Fig 2.1: Co-ordinated Interference

Non- Coordinated: These types of links are further dived into three categories:

Information Asymmetric (IA):

A link l (i, j) experiences Information Asymmetry problem from a link I° (i°, j°) if the following geometric relationships among the sender and receiver of both links are satisfied:

1. distance (i, i°) > Rs : transmitters are not in range of each other.
2. distance (j, i°) < Rs : the receiver of link l is in the range of the transmitter of link l°.
3. distance (i, j°) > Rs : the receiver of link l° is out of range for the transmitter of link l.

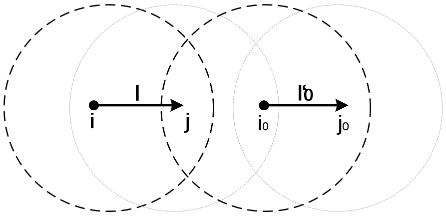


Fig 2.2: Information Asymmetric

Near hidden (NH):

This type of terminal losses occur in between two links l(i, j) and l°(i°, j°) when the links are positioned in such a way that the following geometric relationships among the stations are satisfied:

1. distance (i, i°) > Rs : transmitters are not in range of each other.
2. distance (j, i°) < Rs : the receiver of link l is in the range of the transmitter of link l°.
3. distance (i, j°) < Rs : the receiver of link l° is in the range of the transmitter of link l.

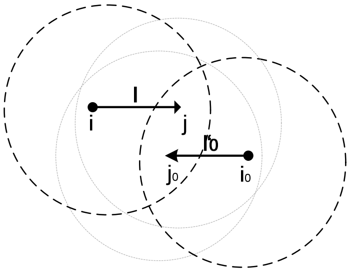


Fig 2.3: Near Hidden

Far hidden (FH):

Far hidden type of terminal losses occur in between two links l(i, j) and l°(i°, j°), when they are arranged in such a way that the following geometric relationships are satisfied:

1) distance (i, i°) > Rs : transmitters are not in the range of each other.
2) distance (j, i°) > Rs or distance (i, j°) > Rs : receivers are not in range of the transmitter of the other flow.
3) distance (i, j°) < Rs : the two receivers are in the range of each other.

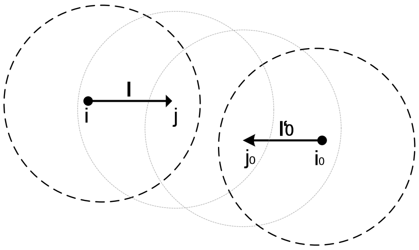


Fig 2.4: Far Hidden

Garetto et al. [7] have also computed that among these two categories non-coordinated interference results in higher transmission losses due to collisions as compared to coordinated interference. This statement naturally gives an idea to a researcher that, if a channel assignment scheme is designed in such a way, which prioritizes the minimization of non-coordinated interference over coordinated interference, then possibly the overall network capacity can significantly be improved.

Naveed [8] proposed interference aware cluster based channel assignment scheme. This method recommends the use of localized default channel in a cluster to broadcasting with minimum overhead. The idea of clustering in WMN has also been employed for routing as well as channel assignment in [18, 19, and 20]. However Naveed [8] presents a novel approach for the minimization of the non-coordinated interference in WMN by using cluster based channel assignment scheme.

By using the clustering approach in channel assignment after partitioning the WMN into non-overlapped clusters, the links can obviously be classified as intra-cluster and inter-cluster links. The inter-cluster links treated as the backbone links between the clusters, are responsible for carrying traffic of several multi-hop flows spanning across multiple clusters.

2.3 Cluster based channel assignment scheme (CCAS)

Cluster based channel assignment scheme (CCAS) proposed by Naveed [8] logically divides the network area into non-overlapping clusters arranged as a hexagonal grid, each cluster have all the nodes located within a single carrier sensing range. With the help of an assumption i.e.

RCS=2RT these nodes can be identified where the transmission range (RT) and carrier sensing range (RCS) of WMN nodes are fixed and all nodes transmit with the same transmission power. Note that the nodes located within a carrier sensing range are circumscribed by a circle with diameter =RCS and radius = RT, as shown in the following Figure 2.5. If a node located at the center of such a circle acting as a cluster head (e.g., node A in Figure 2.5) broadcasts the JOIN message to single hop neighbors, all nodes receiving this message will be located within the distance of one carrier sensing range. CCAS use four orthogonal channels as default channel for the seven clusters placed in the hexagonal grid. In the fig c1, c2, c3, c4, c5 are orthogonal channels used for channel assignment.

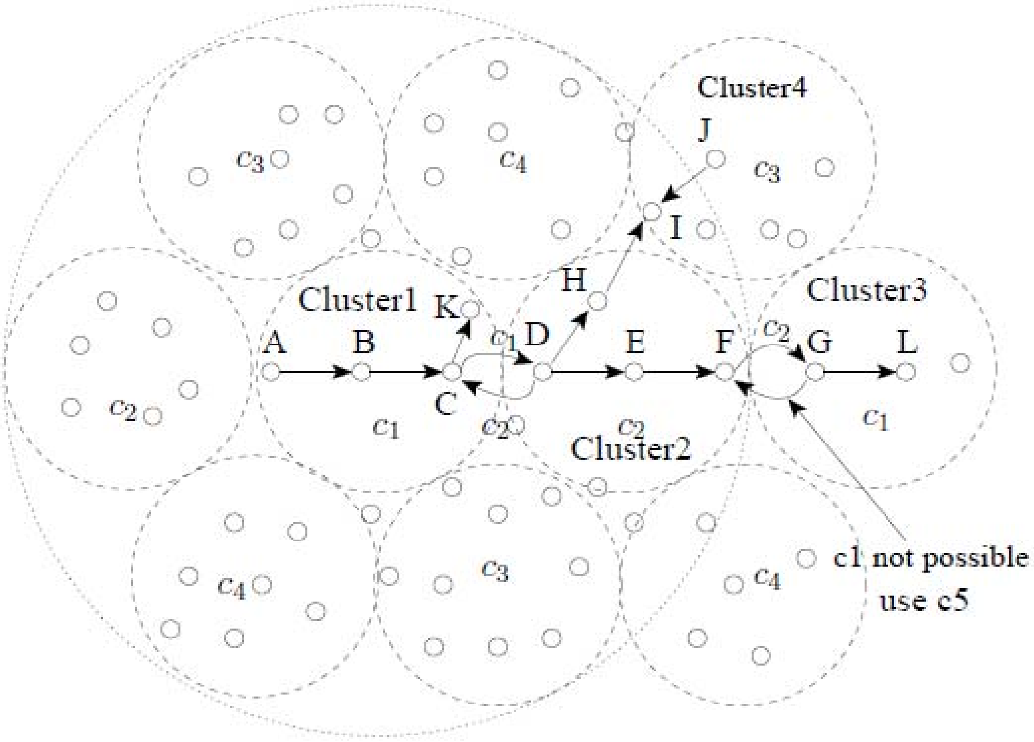


Fig 2.5: CCAS Algorithm [8]

In CCAS for the minimization of non-coordinated interference one interface of each node within a cluster is tuned to a common channel. In this way, all nodes within the cluster can communicate with each other over a common (default) channel. The neighboring clusters use orthogonal channels as their default channel to minimize inter-cluster interference. According to the definition of coordinated interference discussed above, the links formed between the nodes, located within a cluster have coordinated interference relationship with each other. Hence no non-coordinated interference is introduced between these links.

CCAS presents a greedy solution to the problem of minimizing non-coordinated interference by assigning channel to the link in a way that this channel is used by the least number of non-coordinated interfering links of the particular link. In order to identify the set of non-coordinated links, the end nodes of each link would need to know the location coordinates of the three hop neighboring nodes. However, it is not always possible to know the exact geometric locations of all neighboring. Clustering the mesh network is an effective strategy for determining the non-coordinated relationships without requiring a node to know of the physical location of its neighbors.

Clustering a WMN is dependent over the hexagonal grid deployment of 7 nodes which can be extended over the entire WMN. Each of these nodes has a diameter of RCS and the distance between these nodes is equal to carrier sensing Range. The deployment location of all of the other mesh nodes does not matter. The circle with diameter = RCS centered at each of the 7 hexagonal grid node will circumscribe the nodes located within a carrier sensing range. In this way the entire WMN can logically be partitioned into non-overlapping tangential clusters, each comprising of the nodes located within a carrier sensing range.

In the next chapter we implement the CCAS algorithm and try to find out the possible interfering links and the possible area of interfering nodes creating that interfering links for the inter-cluster links, which are responsible of carrying the flows between the clusters.

Chapter 03

Non-Coordinated Inter-Cluster Interfering Links Analysis

The focus of the following chapter is to discuss the detail analysis of non-coordinated interfering inter-cluster links. The discussion is based on separate analysis of all types of non-coordinated interference and their individual effect on inter-cluster links. For this analysis we have considered two contexts of node deployment for the WMN deployed on CCAS algorithm i.e. full mesh node deployment and multiple random deployments of nodes.

The reason of this analysis is to find answers of questions like:

- How many no of inter-cluster links are interfering in each type of non-coordinated interference for each inter-cluster link.
- Where these interfering inter-cluster links are (concerned about the positioning of links) and what is the probability of finding an interfering inter-cluster link there.
- How many no of nodes involved in establishing these interfering inter-cluster links,
- Where these nodes positioned and what is the probability of finding the node there.

3.1 Formation of Inter-cluster Interfering Links

All the possible directional links are formed with the pair of nodes by scanning each node within its transmission range and finding the possible receiver node. As our research focus is only on inter cluster links hence only that pairs of nodes are of interest for the formation of links where sender and receiver nodes are located in opposite neighboring clusters.

After enlisting all the possible inter-cluster links we start finding the possible patterns of Far Hidden, Information Asymmetric and Near Hidden for each link. The implementation of these types is done mathematically in MATLAB according to their definition at section 2.2. According to the deployment of WMN with CCAS algorithm, there are 24 possible directional pairs of clusters for the formation of inter-cluster links as shown in Fig 3.1.

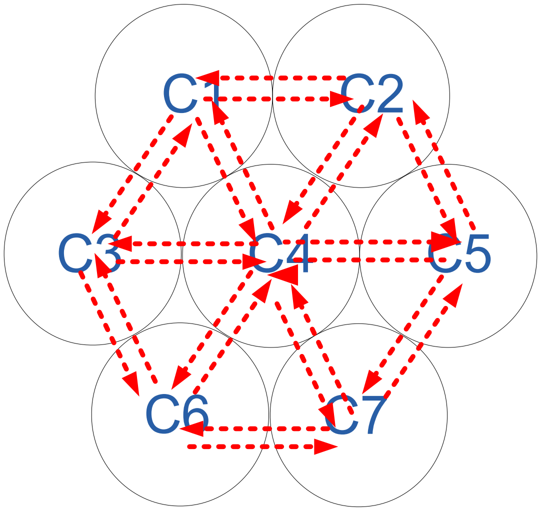


Fig 3.1: Inter-Cluster Links

Among all of these pairs we have found only 03 distinct pairs of cluster for analysis i.e. from top to bottom are C1→C2, C3→C4 and C4→C5. All the other pairs can be adjusted accordingly by just rotating the grid. Like if the grid is rotated anticlockwise then the matching patterns for C1→C2 are C2→C5, C5→C7, C7→C6, C6→C3 and C3→C1, if it is rotated clockwise then the pair of clusters C2→C1, C5→C2, C7→C5, C6→C7, C3→C6 and C1→C3 have the equivalent results. The inner-bound inter-cluster link C3→C4 can be matched with C6→C4, C7→C4, C5→C4, C2→C4 and C1→C4. In the same manner outer-bound link C4→C5 can be matched with C4→C1, C4→C2, C4→C3, C4→C6 and C4→C7.

3.2 Full mesh Analysis

The objective of Full mesh analysis is to find out the all possible interfering links for every inter-cluster link exists in the grid of seven clusters. Later in the extension of this analysis we also find out the possible interfering area and the no of interfering nodes constructing these interfering links for inter-cluster links.

By using MATLAB, each type of Non-coordinated interference is mathematically implemented on a grid as shown in the following Fig 3.2. The node deployment in the grid is in full mesh with all possible nodes in the clusters. The blocks are the representation of the nodes chosen on a network area. The logical boundaries of the clusters are represented with the pink blocks encompasses nodes within the circumference of a cluster. The diameter of the cluster is equivalent to the carrier sensing range (RCS) and the radius is equivalent to the transmission range (RT) of a node.

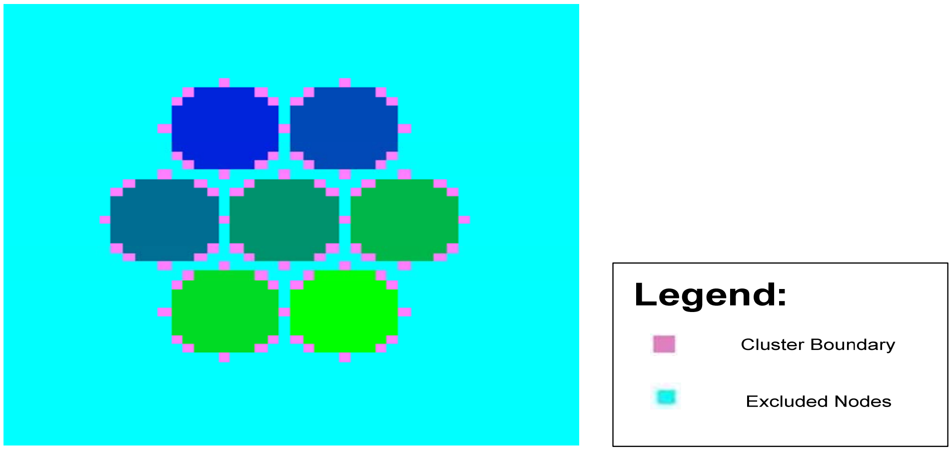


Fig 3.2: Full Mesh Analysis

3.2.1 Percentage of non coordinated interfering links

In order to effectively eliminate the non-coordinated inter-cluster interference with limited amount of available channels, it is important to identify the no of inter-cluster interfering links from each pair cluster. In the following sections we present the individual analysis of all types of non-coordinated interference found for the inter-cluster links. As discussed above we have considered only three pairs of inter-cluster links i.e. C1→C2, C3→C4 and C4→C5.

3.2.1.1 C1→C2 Pattern Analysis

In Fig 3.3 the pattern is shown for the inter-cluster links between clusters C1→C2. There are total no of 218 inter-cluster links have been found in between clusters C1→C2. The total no of corresponding FH and IA interfering links are 14,558, and NH links are 17359. The locations of all of these possible interfering links for C1→C2 are shown with dotted directional arrows in between the clusters.

In Fig 3.3a the FH interfering links are shown at C3→C4, C4→C5, C4→C3, C4→C2, C5→C2, C5→C4, C6→C4, C7→C4 and C7→C5.

In Fig 3.3b the IA interfering links are shown at C3→C4, C4→C5, C4→C3, C2→C4, C2→C5, C5→C4, C4→C6, C4→C7 and C5→C7.

In Fig 3.3c the NH interfering links are shown at C2→C4, C3→C1, C3→C4, C4→C3, C4→C1, C4→C2, C4→C5, C5→C4 and C5→C2.

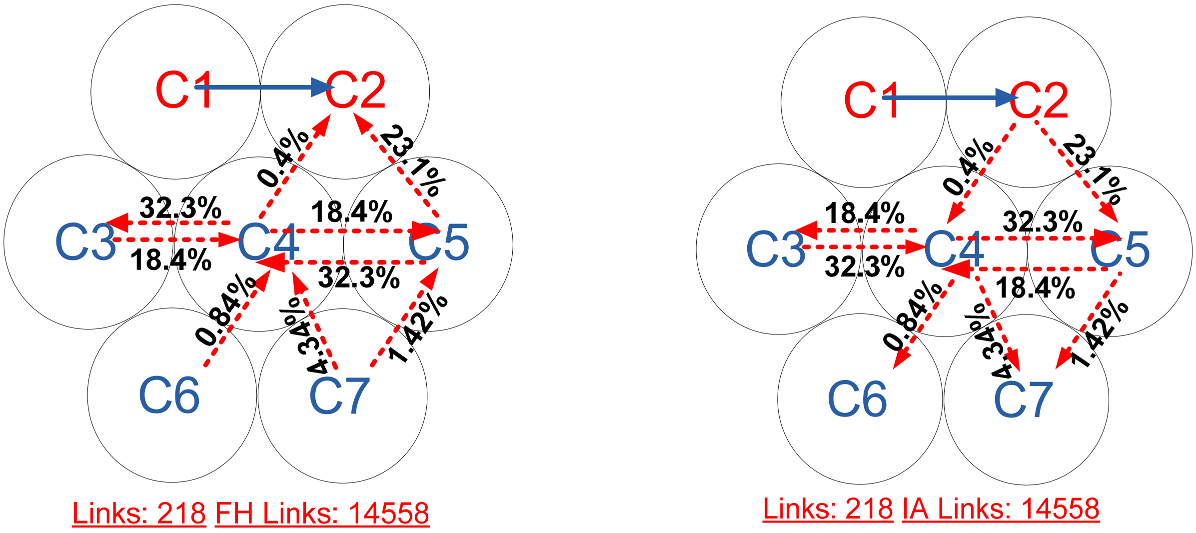


Fig 3.3a: FH Analysis

Fig 3.3b: IA Analysis

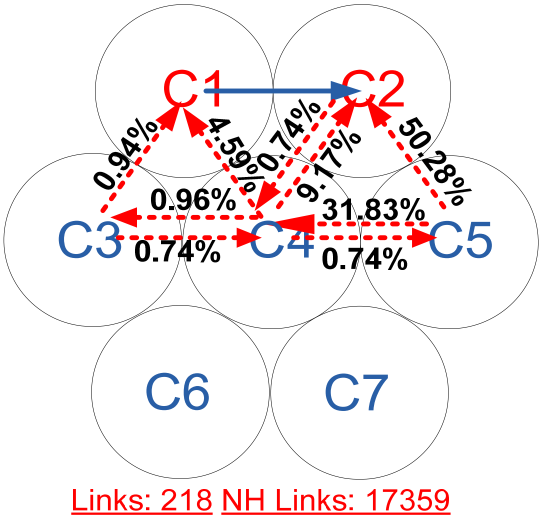


Fig 3.3c: NH Analysis

Fig 3.3: Interfering Inter-cluster links locations for C1→C2

The no of interfering inter-cluster links and its percentage (computed along the total no of interfering links found) of each type are shown in table 3.1

While evaluating the above analysis collectively, a very basic idea comes into the mind that the area where there are very less interfering links or where the %ge of interfering links <5%; the happening of inter-cluster interfering links is also rare. Hence the assignment of channel to that inter-cluster links can be skipped by eliminating the paths of the inter-cluster flows and rerouting the paths from other inter-cluster links. In this way we can save the channels and reuse them for some other inter-cluster links where the concentration of interfering links is very high i.e. >10%.

Cluster	**FH**		**IA**		**NH**	
	# of Links	**%ge**	**# of Links**	**%ge**	**# of Links**	**%ge**
C1→C2	0	0.00	0	0.00	0	0.00
C1→C3	0	0.00	0	0.00	0	0.00
C1→C4	0	0.00	0	0.00	0	0.00
C2→C1	0	0.00	0	0.00	0	0.00
C2→C4	0	0.00	67	0.46	129	0.74
C2→C5	0	0.00	3364	23.11	0	0.00
C3→C1	0	0.00	0	0.00	164	0.94
C3→C2	0	0.00	0	0.00	0	0.00
C3→C4	2682	18.42	101	0.69	129	0.74
C4→C1	0	0.00	0	0.00	797	4.59
C4→C2	67	0.46	0	0.00	1592	9.17
C4→C3	101	0.69	2682	18.42	166	0.96
C4→C5	2662	18.42	4701	32.29	129	0.74
C4→C6	0	0.00	122	0.84	0	0.00
C4→C7	0	0.00	632	4.34	0	0.00
C5→C2	3364	23.11	0	0.00	8728	50.28
C5→C4	4701	32.29	2662	18.42	5526	31.83
C5→C7	0	0.00	207	1.42	0	0.00
C6→C3	0	0.00	0	0.00	0	0.00
C6→C4	122	0.84	0	0.00	0	0.00
C6→C7	0	0.00	0	0.00	0	0.00
C7→C4	632	4.34	0	0.00	0	0.00
C7→C5	207	1.42	0	0.00	0	0.00
C7→C6	0	0.00	0	0.00	0	0.00

Table 3.1: # of interfering inter-cluster links for C1→C2

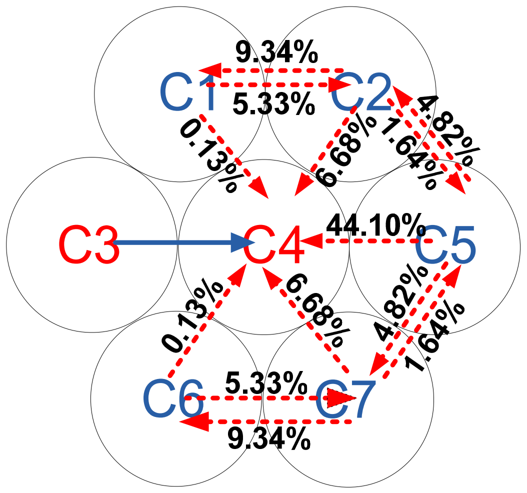
3.2.1.2 C3→C4 Pattern Analysis

In Fig 3.4 the pattern is shown for the inter-cluster links between clusters C3→C4. There are total no of 218 inter-cluster links have been found in between clusters C3→C4. The total no of corresponding FH and IA interfering links are 50,328, and NH links are 43,658. The locations of all of these possible interfering links for C3→C4 are shown with dotted directional arrows in between the clusters.

In fig 3.4a the FH interfering links are shown at C1→C4, C1→C2, C2→C1, C2→C4, C2→C5, C5→C2, C5→C4, C5→C7, C6→C4, C6→C7, C7→C4, C7→C5 and C7→C6.

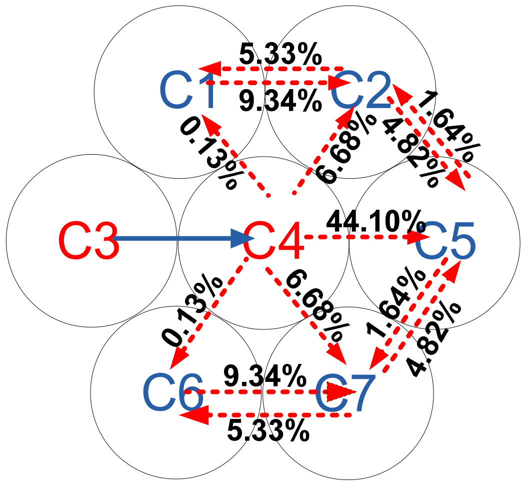
In fig 3.4b the IA interfering links are shown at C4→C, C1→C2, C2→C1, C4→C2, C2→C5, C5→C2, C4→C5, C5→C7, C4→C6, C6→C7, C4→C7, C7→C5 and C7→C6.

In fig 3.4c the NH interfering links are shown at C1→C4, C1→C2, C1→C3, C2→C1, C2→C4, C5→C4, C6→C4, C4→C6, C6→C7, C7→C4, C6→C3 and C7→C6.



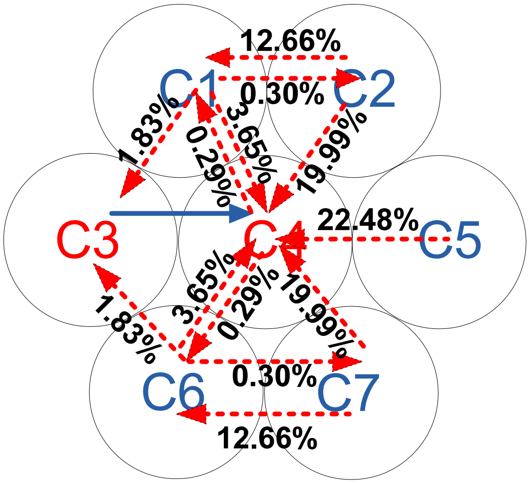
Links: 218 FH Links: 50328

Fig 3.4a: FH Analysis



Links: 218 IA Links: 50328

Fig 3.4b: IA Analysis



Links: 218 NH Links: 43658

Fig 3.4c: NH Analysis

Fig 3.4: Interfering Inter-cluster links locations for C3→C4

The no of interfering inter-cluster links and its percentage (computed along the total no of interfering links found) are shown in the following table 3.2

Cluster Pair	**FH**		**IA**		**NH**	
	# of Links	**%ge**	**# of Links**	**%ge**	**# of Links**	**%ge**
C1→C2	2682	5.33	4701	9.34	129	0.30
C1→C3	0	0.00	0	0.00	797	1.83
C1→C4	67	0.13	0	0.00	1592	3.65
C2→C1	4701	9.34	2682	5.33	5526	12.66
C2→C4	3364	6.88	0	0.00	8728	19.99
C2→C5	824	1.64	0	0.00	0	0.00
C3→C1	0	0.00	0	0.00	0	0.00
C3→C2	0	0.00	0	0.00	0	0.00
C3→C4	0	0.00	0	0.00	0	0.00
C4→C1	0	0.00	67	0.13	129	0.30
C4→C2	0	0.00	3364	6.88	0	0.00
C4→C3	0	0.00	0	0.00	0	0.00
C4→C5	0	0.00	22196	44.10	129	0.30
C4→C6	0	0.00	67	0.13	0	0.00
C4→C7	0	0.00	3364	6.88	0	0.00
C5→C2	0	0.00	824	1.64	22	0.05
C5→C4	22196	44.10	0	0.00	9814	22.48
C5→C7	2428	4.82	824	1.64	22	0.05
C6→C3	0	0.00	0	0.00	797	1.83
C6→C4	67	0.13	0	0.00	1592	3.65
C6→C7	2682	5.33	4701	9.34	129	0.30
C7→C4	3364	6.88	0	0.00	8728	19.99
C7→C5	824	1.64	2428	4.82	0	0.00
C7→C6	4701	9.34	0	0.00	5526	12.66

Table 3.2: # of interfering inter-cluster links for C3→C4

3.2.1.3 C4→C5 Pattern Analysis

In Fig 3.5 the pattern is shown for the inter-cluster links between clusters C4→C5. There are total no of 218 inter-cluster links have been found in between clusters C4→C5. The total no of corresponding FH and IA interfering links are 5,704, and NH links are 5,952. The locations of all of these possible interfering links for C4→C5 are shown with dotted directional arrows in between the clusters.

In fig 3.5a the FH interfering links are shown at C1→C2, C2→C1, C2→C5, C3→C1, C3→C6, C6→C7, C7→C6 and C7→C5.

In fig 3.5b the IA interfering links are shown at C1→C2, C2→C1, C5→C2, C1→C3, C6→C3, C6→C7, C7→C6 and C5→C7.

In fig 3.5c the NH interfering links are shown at C1→C2, C2→C1, C2→C5, C5→C2, C1→C4, C2→C4, C6→C4, C7→C4, C6→C7, C7→C6, C5→C7 and C7→C5.

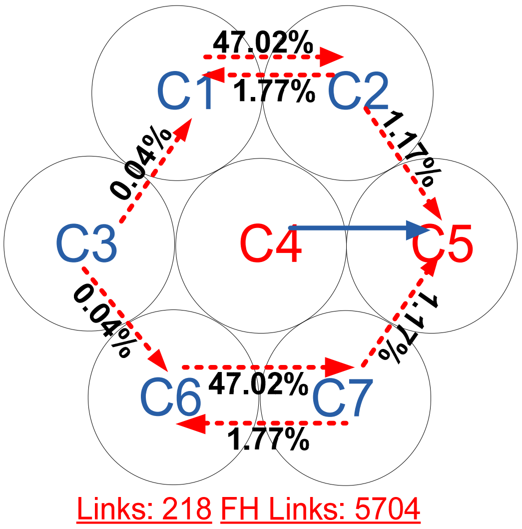


Fig 3.5a: FH Analysis

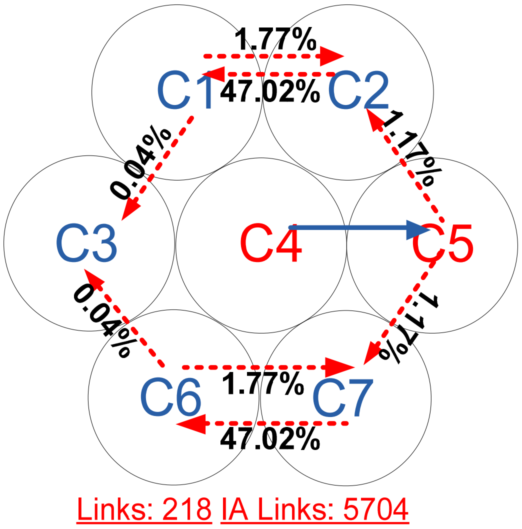
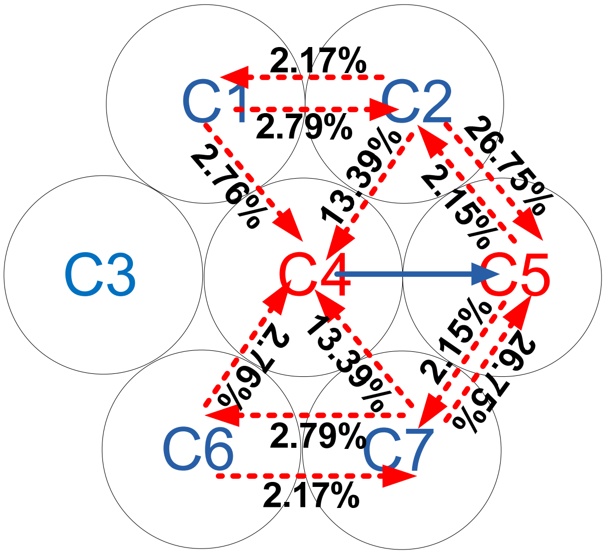


Fig 3.5b: IA Analysis



Links: 218 NH Links: 5952

Fig 3.5c: NH Analysis

Fig 3.5: Interfering Inter-cluster links locations for C4→C5

The no of interfering inter-cluster links and its percentage (computed along the total no of interfering links found) are shown in the following table 3.3

An observation which can easily be determined through the above analysis and is clearly confirmed from viewing the figures of interfering inter-cluster link locations for C3→C4 and C4→C5 (fig 3.4a and fig 3.5a of FH analysis and fig 3.4b and fig 3.5b of NH analysis); that the lower half of the grid is exactly the opaque of the upper half. This leads us to a concept of using the same channels for the upper half and lower half, e.g. the channel used for C1→C2 can also be utilized for the C6→C7.

Cluster Pair	**FH**		**IA**		**NH**	
	# of Links	**%ge**	**# of Links**	**%ge**	**# of Links**	**%ge**
C1→C2	2682	47.102	101	1.77	129	2.17
C1→C3	0	0.00	2	0.04	0	0.00
C1→C4	0	0.00	0	0.00	164	2.76
C2→C1	101	1.77	2682	47.102	166	2.79
C2→C4	0	0.00	0	0.00	797	13.39
C2→C5	67	1.17	0	0.00	1592	26.75
C3→C1	2	0.04	0	0.00	0	0.00
C3→C2	0	0.00	0	0.00	0	0.00
C3→C4	0	0.00	0	0.00	0	0.00
C3→C6	2	0.04	0	0.00	0	0.00
C4→C1	0	0.00	0	0.00	0	0.00
C4→C2	0	0.00	0	0.00	0	0.00
C4→C3	0	0.00	0	0.00	0	0.00
C4→C5	0	0.00	0	0.00	0	0.00
C4→C6	0	0.00	0	0.00	0	0.00
C4→C7	0	0.00	0	0.00	0	0.00
C5→C2	0	0.00	67	1.17	128	2.15
C5→C4	0	0.00	0	0.00	0	0.00
C5→C7	0	0.00	67	1.17	128	2.15
C6→C3	0	0.00	2	0.04	0	0.00
C6→C4	0	0.00	0	0.00	164	2.76
C6→C7	2682	47.102	101	1.77	129	2.17
C7→C4	0	0.00	0	0.00	797	13.39
C7→C5	67	1.17	0	0.00	1592	26.75
C7→C6	101	1.77	2682	47.102	166	2.79

Table 3.3: no of interfering inter-cluster links for C4→C5

3.2.1.4 Discussion

The above analysis clearly shows that for a given link, the interfering FH and IA directional links are always reverse of each other. This leads us to an idea that elimination of one type can automatically eliminate the other. In this way, while assigning channel for a link, we have to focus only on two types of non-coordinated interfering links i.e. the Near hidden Links and the merger of Information Asymmetric and Far hidden links. Hence non-directional channel assignment is possible and can achieve better results as compared to unidirectional channel assignment. On the basis of this, in further analysis we have only focused upon Far hidden and Near hidden types of non-coordinated interference and omitted the Information Asymmetric type.

3.2.2 Probability of Inter-cluster Interfering Nodes

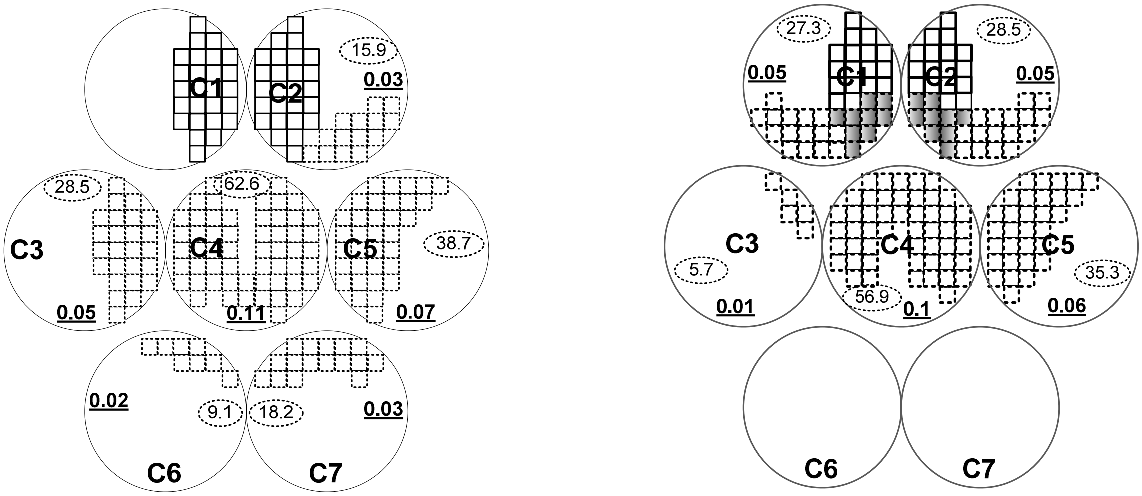
After the estimation of possible inter-cluster interfering links the next important step is to find out the probability of those interfering nodes, who act as a sender or receiver of that links. This step leads us to calculate that exact area in every cluster where these interfering nodes converged, if a particular interfering inter-cluster link occurs.

There are total no of 483 nodes placed on the grid equally divided into seven clusters (69 nodes per cluster). For establishing the links between C1→C2, C3→C4 and C4→C5 there are 26 nodes on each side located in the clusters. The probability of finding the interfering node in an individual cluster in the selected grid is computed and shown in the following figs marked with underline.

The area of the grid encompasses by the placement of 483 nodes is ‘549.78’. The subsequent areas for interfering nodes in each cluster are also calculated and shown in the following figs in this section marked with ellipses.

3.2.2.1 C1→C2 Interfering Inter-Cluster Nodes Analysis

In Fig 3.6 the pattern is shown for the inter-cluster nodes between clusters C1→C2. From FH analysis, 212 interfering nodes have been found in the clusters C2, C3, C4, C5, C6 and C7 acting as the source for the inter-cluster interfering links. Similarly from NH analysis 135 interfering nodes are discovered in C2, C3, C4 and C5. The locations of all of these specific interfering nodes for C1→C2 inter-cluster links are shown with dotted boxes in the clusters. The boxes with solid lines show the placement of nodes for inter-cluster links for C1→C2. In case of NH interference the shaded boxes demonstrate the nodes acting as both the interfering node and either acting as a sender or receiver for the link between C1→C2.



Total Area: 549.8 Interfering Nodes: 212

Fig 3.6a: FH Nodes

Total Area: 549.8 Interfering Nodes: 135

Fig 3.6b: NH Nodes

Fig 3.6: Interfering Nodes for Inter-Cluster links in C1→C2

The above information in the Fig 3.6 is also summarized in the following table 3.4 with the no of nodes found in each cluster for FH and NH interfering inter-cluster links. Similarly the probability and area for the interfering nodes of inter-cluster links in between C3→C4 and C4→C5 are computed and shown in the tables 3.5 and 3.6.

Cluster	**FH Link Nodes**			**NH Link Nodes**		
	# of Nodes	**Probability**	**Area**	**# of Nodes**	**Probability**	**Area**
C1	0	0.00	0	24	0.3	27.3
C2	14	0.2	15.9	25	0.4	28.5
C3	25	0.4	28.5	5	0.1	5.7
C4	55	0.8	62.6	50	0.7	56.9
C5	34	0.5	38.7	31	0.4	35.3
C6	8	0.1	9.1	0	0.00	0.0
C7	16	0.2	18.2	0	0.00	0.0

Table 3.4: Analysis of Interfering Inter-cluster Nodes for C1→C2

3.2.2.2 C3→C4 Interfering Inter-Cluster Nodes Analysis

Cluster	**FH Link Nodes**			**NH Link Nodes**		
	# of Nodes	**Probability**	**Area**	**# of Nodes**	**Probability**	**Area**
C1	27	0.4	30.5	40	0.6	45.5
C2	41	0.6.	46.3	31	0.4	35.3
C3	0	0	0	34	0.5	38.7
C4	36	0.5	40.7	58	0.8	66.0
C5	40	0.6	45.2	26	0.4	29.6
C6	27	0.4	30.5	40	0.6	45.5
C7	41	0.6	46.3	31	0.4	35.3

Table 3.5: Analysis of Interfering Inter-cluster Nodes for C3→C4

3.2.2.3 C4→C5 Interfering Inter-Cluster Nodes Analysis

Cluster	FH Link Nodes			NH Link Nodes		
	# of Nodes	Probability	Area	# of Nodes	Probability	Area
C1	25	0.4	28.4	5	0.1	5.7
C2	31	0.4	35.3	35	0.5	39.8
C3	4	0.1	4.6	0	0.00	0.0
C4	0	0.00	0.0	48	0.7	54.6
C5	10	0.1	11.4	34	0.5	38.7
C6	25	0.4	28.4	5	0.1	5.7
C7	31	0.4	35.3	35	0.5	39.8

Table 3.6: Analysis of Interfering Inter-cluster Nodes for C4→C5

3.2.2.4 Discussion

Through the above analysis we have computed the exact placement of interfering nodes on the grid for any inter-cluster link. This computation further facilitates us in the elimination of non-coordinated interference, as prior to the assignment of channels to the inter-cluster links the non-coordinated interference can be predicated for any inter-cluster link takes place in the WMN. Basically now we have the exact information of every possible interfering node, and also we have computed the exact area where the possibility of happening of that node exists.

3.3 Random Deployment Analysis

In this section we try to simulate the actual field deployment of nodes in WMN using CCAS algorithm. We have done almost 10 to 15 iterations using MATLAB and by taking the random deployment of nodes. Each type of Non-coordinated interference is mathematically implemented on the randomly selected grid; one of the deployments is shown in the Fig 3.7. The blocks are the representation of the nodes chosen on a network area. The logical boundaries of the clusters are represented with the pink blocks encompasses nodes within the cluster. In the random iterations we have tried to pick only that where the node concentration in every cluster is in average 16 to 17.

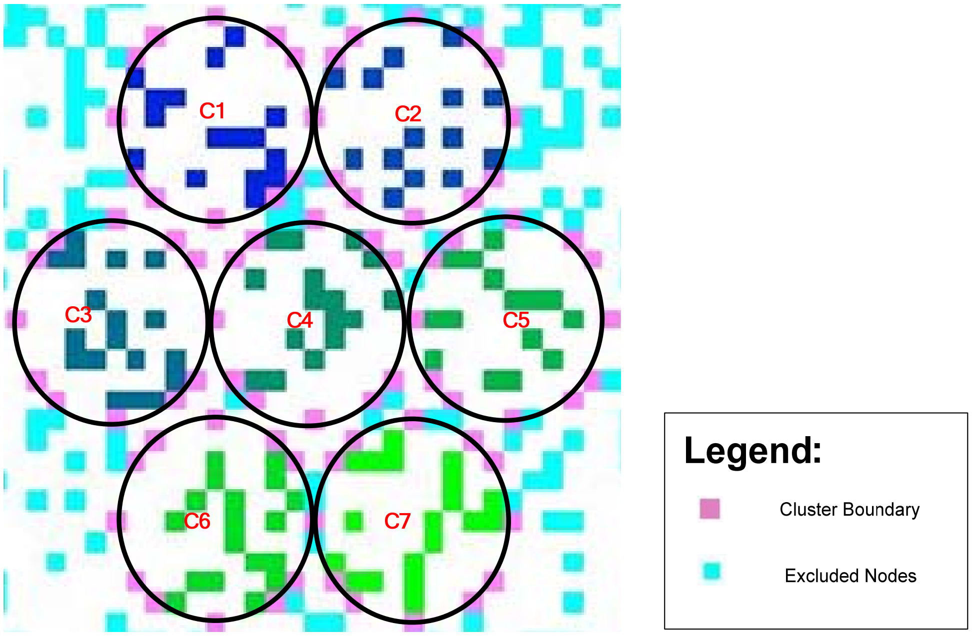
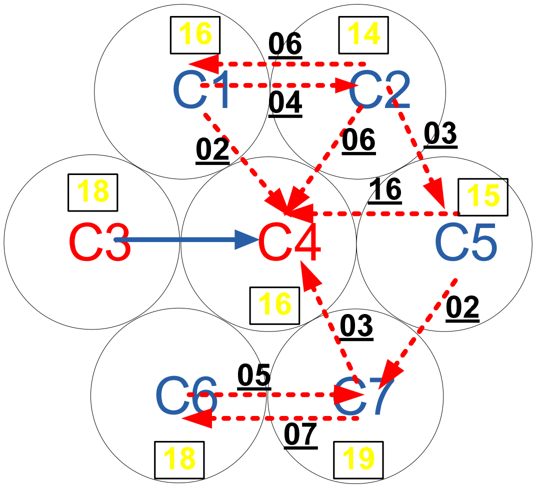


Fig 3.7: Random Deployment of Nodes

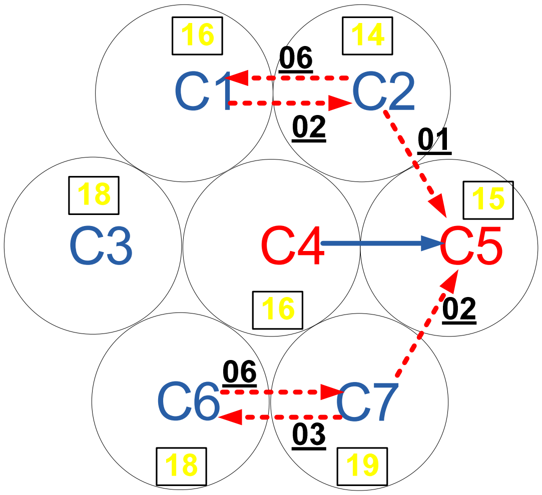
For the analysis we have chosen C3→C4, C4→C5 and instead of C1→C2 we have chosen C6→C7 to test the claim which we initially made in section 3.1 that the results of the outer inter-cluster links are the same as of C1→C2.

Below are the average FH and NH analysis of the inter-cluster links for random deployment. The no of nodes randomly deployed in every cluster is mentioned inside the boxes and the no of interfering links found is underlined in the fig 3.8 and 3.9.



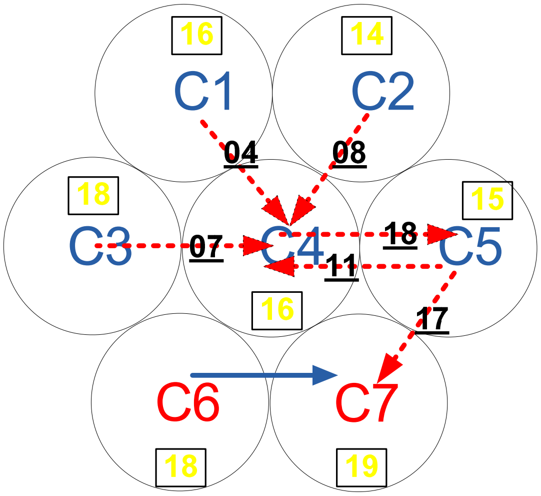
Links:07 FH Links:54

Fig 3.8a: FH Random Analysis for C3→C4



Links: 13 FH Links: 20

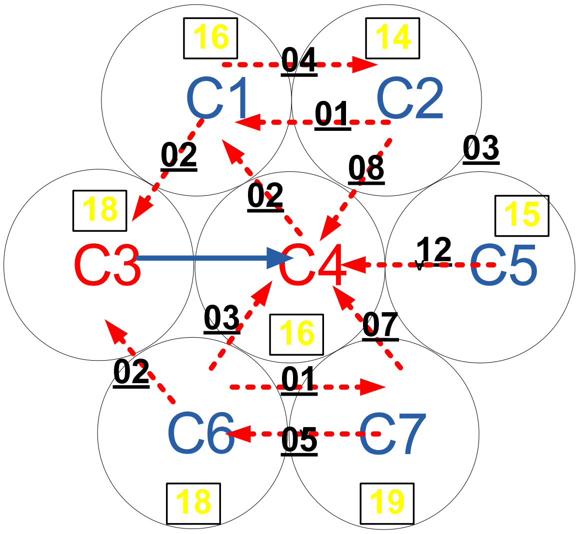
Fig 3.8b: FH Random Analysis for C4→C5



Links: 25 FH Links: 66

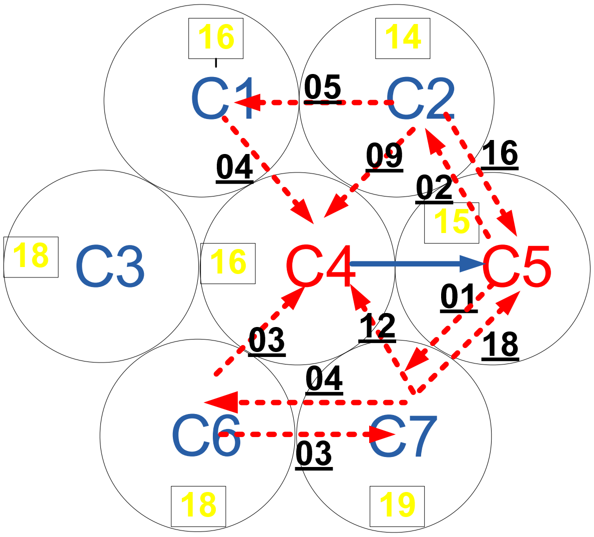
Fig 3.8c: FH Random Analysis for C6→C7

Fig 3.8: FH Analysis in Random Deployment of Nodes



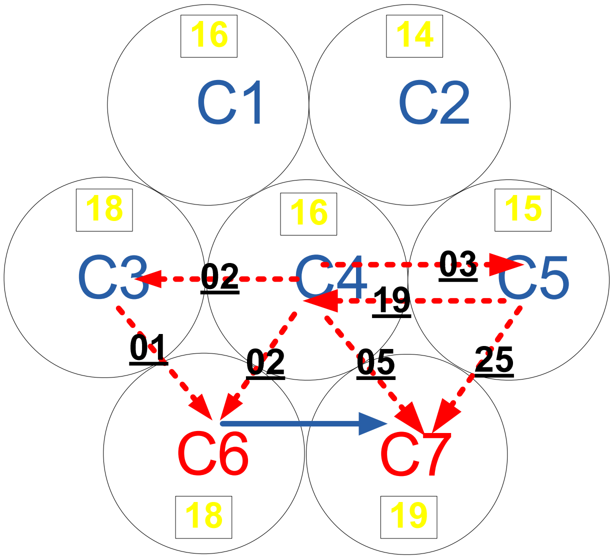
Links: 13 NH Links: 30

Fig 3.9a: NH Random Analysis for C3→C4



Links: 07 FH Links: 54

Fig 3.9b: NH Random Analysis for C4→C5



Links: 25 NH Links: 41

Fig 3.9c: NH Random Analysis for C6→C7

Fig 3.9: NH Analysis in Random Deployment of Nodes

The above random analysis approximately follows the same pattern as we have explored in the full mesh node deployment.

Base on the above discussion and observations, in the next chapter we proposed a channel assignment scheme and simulated it in OPNET simulator to find out its impact on overall performance of the a wireless mesh network.

Chapter 04

Channel Assignment Scheme for Inter-cluster Links

In the following chapter we have proposed a channel assignment scheme for inter-cluster links. We have then simulated a WMN network with that scheme in OPNET simulator. The simulation results have also been discussed in this chapter.

4.1 Proposed Channel Assignment Scheme

We have proposed an inter-cluster channel assignment scheme on top of CCAS by utilizing 4 additional orthogonal channels (Fig 4.1). The proposed scheme exploits the trade-off between numbers of inter-cluster links and introduced non-coordinated interference. A sub-set of inter-cluster links is assigned orthogonal channels, while remaining inter-cluster links are not assigned any channel. The scheme results in replacing certain inter-cluster links with the set of links have path length of up to 3.

This channel assignment scheme is exactly based upon the results achieved in the analysis of inter-cluster interfering links in chapter 03. As we have spotted the areas in the analysis where there is very low concentration of nodes, now that subsets of inter-cluster links are being skipped in this proposed channel assignment scheme. The channels are also being utilized in upper and lower half of the grid based upon the observations in the analysis. So with the help of only 4 channels the channels are assignment to all of the inter-cluster links existing in the grid of seven clusters.

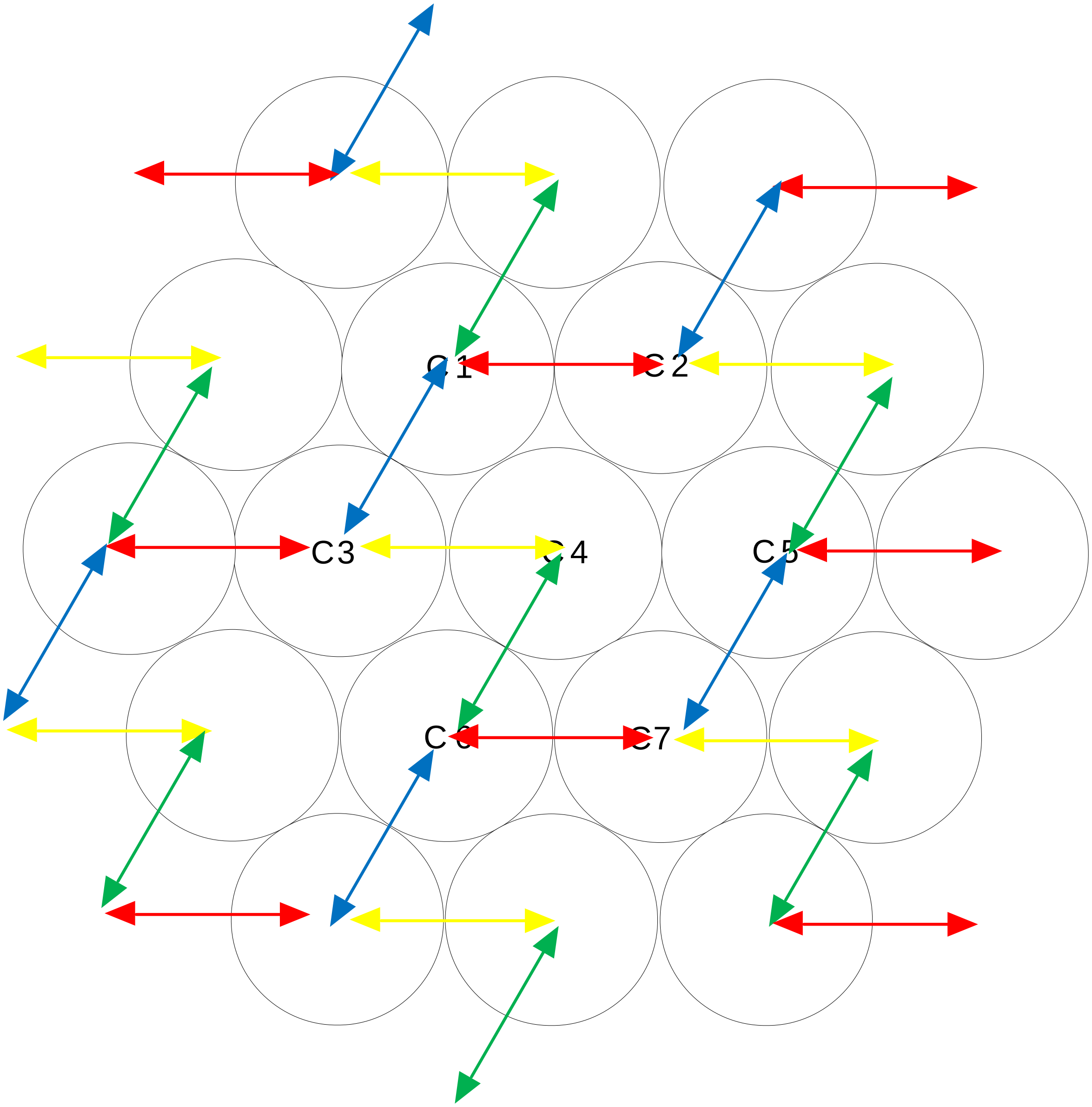


Fig 4.1: Proposed Channel Assignment Scheme

4.2 Simulation

The effectiveness of the proposed inter-cluster channel assignment scheme in improving the overall network throughput has been tested in OPNTET simulator. We have considered four end-to-end multi-hop flows extending over multiple clusters. The network which we have constructed in OPNET simulator by randomly placing the nodes is shown in the following Figure 4.2:

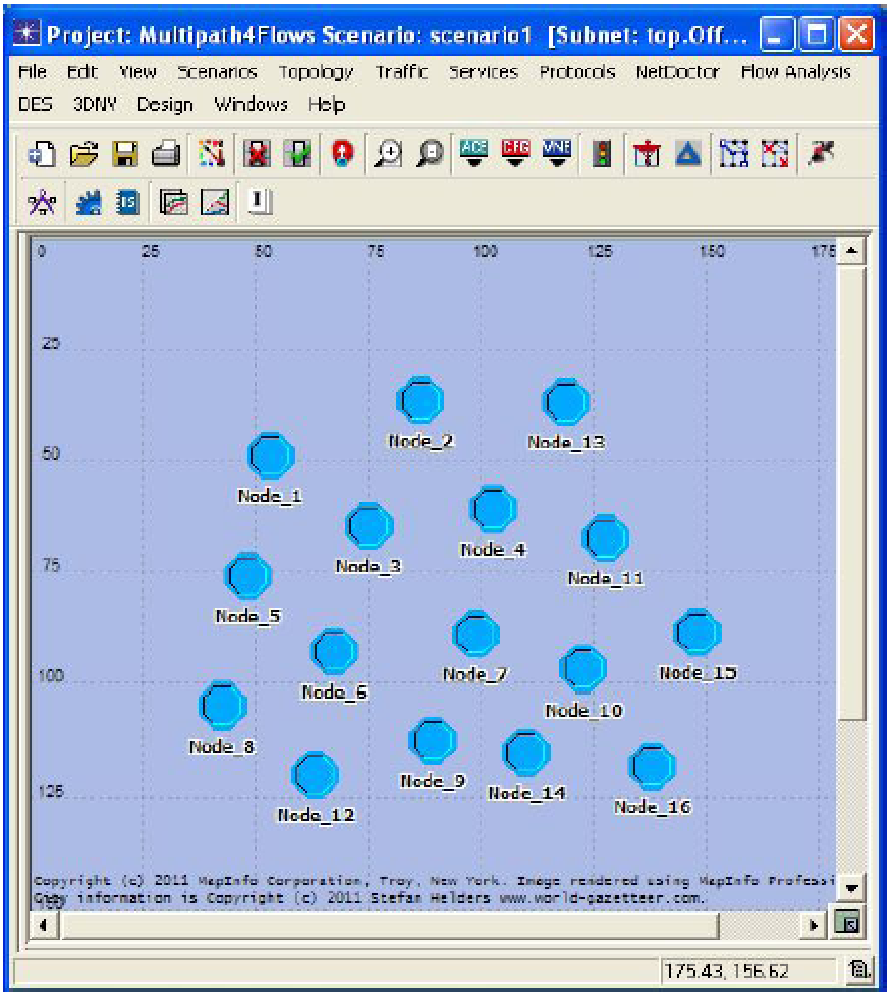


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Fig 4.2: Random Placement of nodes in OPNET Simulator

The parameters used for simulation are shown in the following Table 4.1. The randomly selected nodes are equipped with 4 radios; this has been accomplished by modifying the node model for the considered MR-MC WMN. Each radio can transmit as well as receive data. In OPNET Simulation is handled by two input files at node model; one file consists of source destination pair nodes and the other file consists of routing table having four fields (Source, Destination, NextHopRadio and Channel). Data traffic with packets of fixed size (i.e. 4096 bits) is generated by using a Poisson traffic generator at the application layer with mean inter-arrival duration of 0.005Sec at each source. This results in saturated traffic load on a wireless link with transmission capacity of 11Mbps. We have used IEEE 802.11a radio interfaces with data transmission rate of 11Mbps.

Radio Type:	IEEE 802.11a
Data Rate:	11 Mbps
Terrain Area:	270m x 270m
Applied Load:	2.2Mbps Unsaturated
No. of Nodes:	12
Node Placement:	Random
No. of Radios:	1/Node
No. of Channels:	4
Transmit Power:	7E-006W [for around 30m]
Packet Reception Power:	-95dB
Packet Size:	4096 bits
Simulation Time:	10 minutes

Table 4.1: Simulation Parameters

4.2.1 Single Flow Simulation

Initially only the single hop inter cluster flows are considered to find the improvement in overall throughput of the network. The network considered for this simulation is shown below in Fig 4.3. The transmission range for each node is 34 and the corresponding carrier sensing range is adjusted to be 90 according to the default behavior of OPNET simulator i.e. RCS = 2.5RT. According to our proposed CA in sec 3.2, we have considered only six inter-cluster flows for simulation. These inter-cluster flows are: Flow 1 in cluster 1 and cluster 2 with source node A & sink node B, Flow 2 in cluster 1 and cluster 3 with source node C & sink node D, Flow 3 in cluster 3 and cluster 4 with source node E & sink node F, Flow 4 in cluster 4 and cluster 5 with source node G & sink node H, Flow 5 in cluster 3 and cluster 6 with source node I & sink node J, Flow 6 in cluster 6 and cluster 7 with source node K & sink node L.

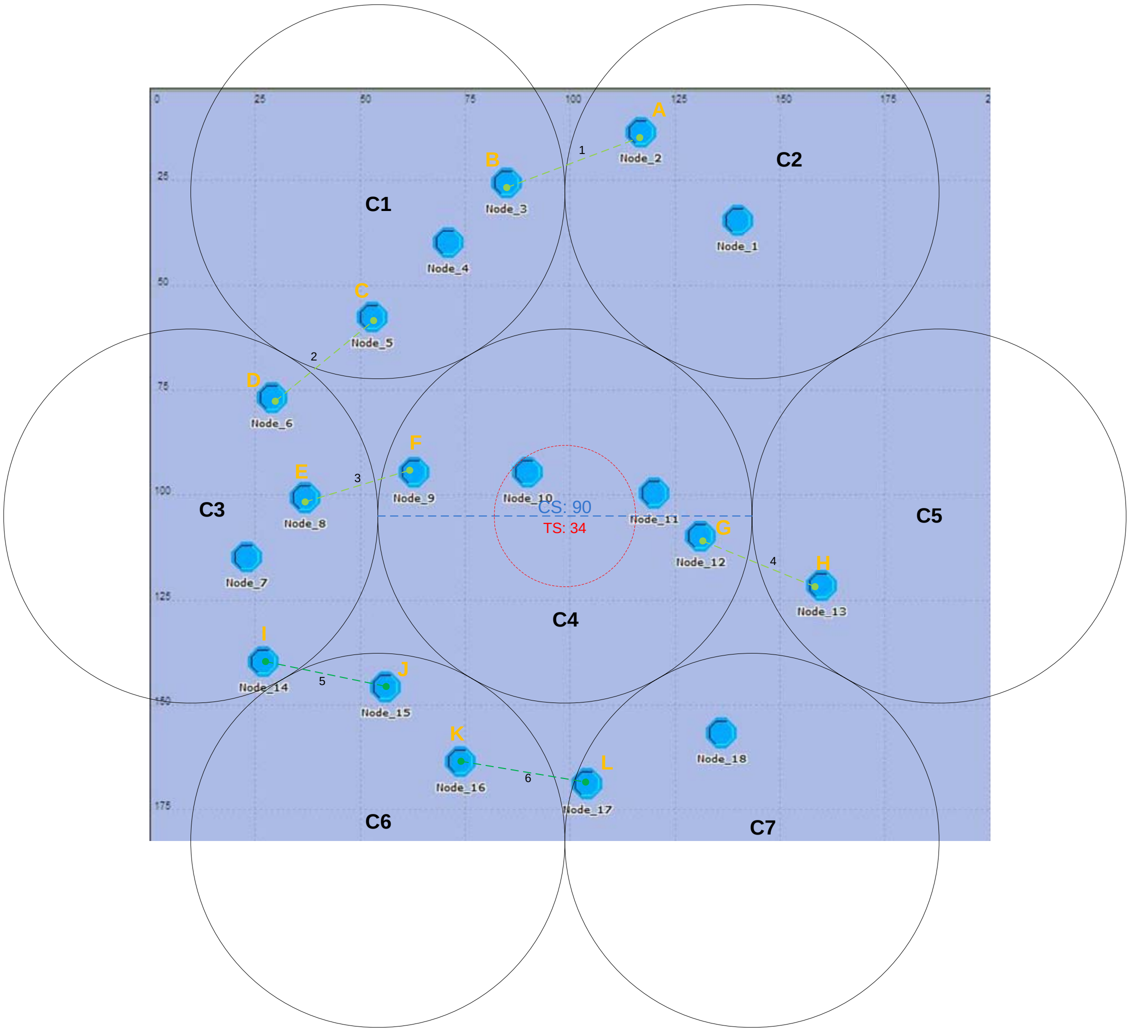
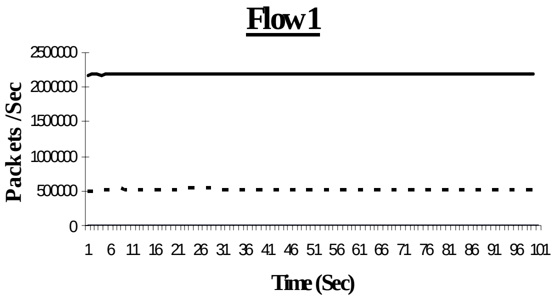


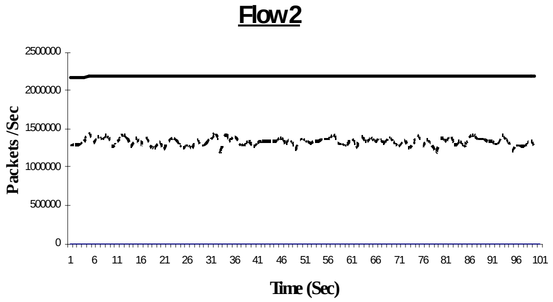
Fig 4.3: Single-Hop Inter-Cluster Flows

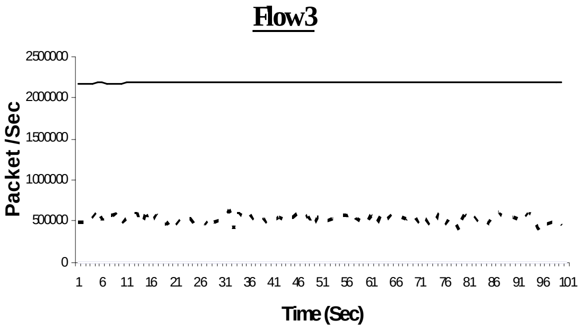
First we simulated the scenario with randomly assigned four channels to the six flows for single-hop inter-cluster communication, and then we assigned the channels according to our proposed channel assignment scheme. Remember these channels are in addition to the four channels already assigned for intra-cluster transmission.

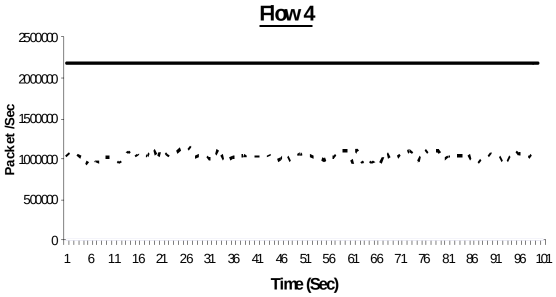
4.2.1.1 Results and Discussion

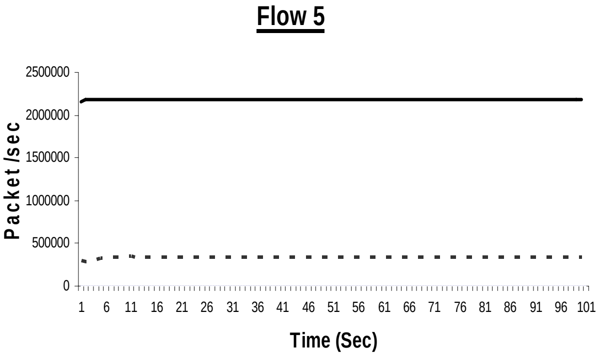
The simulation results for all single flows are shown in Fig 4.3. In the graph alongside x-axis we have the time bar in seconds and on the y-axis we have number of packets per second. Each line in the graph represents number of packets received at destinations for that flow. The dotted line shows the throughput achieved while the channels are randomly assigned to the inter-cluster flows and solid line for the throughput attained after the assignment of channels according to our proposed channel assignment scheme. The duration for simulation is ten minutes for steady and stable results.

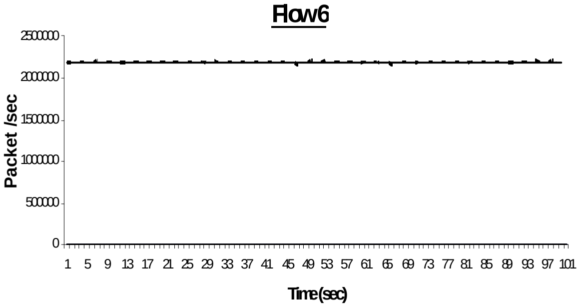












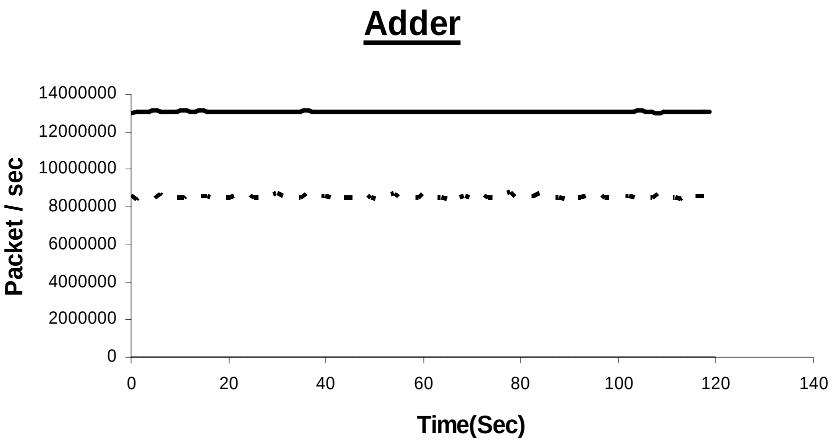


Fig 4.4: Simulation Results for Single Flow Analysis

The above results show a significant improvement in the throughput of single flows for inter-cluster links, while the channels are assigned according to our proposed channel assignment scheme. The Adder graph shows the added throughput of all single flows with almost 12% improvement.

4.2.2 End to End Flow Simulation

In the next phase of simulation we have created three end-to-end flows by incorporating both intra-cluster and inter-cluster links. This situation creates a simulated environment of the actual deployment of WMN in the field, in which there are multiple flows traversing along the network encompassing various nodes. The transmission and carrier sensing ranges are the same as in the previous simulation i.e. 34 and 90 respectively.

The flows are: Flow 1 is from cluster 2 to cluster 3 with source node A & sink node B and passes through Cluster 1, Flow 2 is from cluster 3 to cluster 5 with source node C & sink node D and passes through Cluster 4, Flow 3 is from cluster 3 to cluster 7 with source node E & sink node F and passes through Cluster 6.

In Flow 1 there are two inter-cluster links at C1→C2 and C1→C3, two intra-cluster links in clusters C2 and one in C1. While in Flow 2 there are two inter-cluster links i.e. C3→C4 and C4→C5, one intra-cluster links in cluster C3 and three intra-cluster links in cluster C4. The remaining flow 3 has two inter-cluster links at C3→C6, C6→C7, and one intra cluster link in both clusters C6, C7 respectively.

First we simulated the scenario with randomly assigned channels to all of the flows including inter-cluster and intra-cluster flows. After that we assigned the channels to the intra-cluster flows according to CCAS algorithm and for inter-cluster flows we applied our proposed channel assignment scheme. In this implementation we have to leave to inter-cluster paths i.e. C4→C5 and C3→C6 as no channel is assigned to these links and follow an alternate path to establish the end-to-end flow for flow 2 & 3. For flow 2 the normal path is altered in C4 and then followed the alternate path traversing through clusters C6, C7 and ends at C5. This involves additional 4 intra-cluster hops and three inter-cluster links. For Flow 3 to follow the alternate path we have to include two additional inter-clusters links i.e. C3→C4, C4→**!Unexpected End of Formula**C6 and one intra-cluster in C3. This path is shorter than the path followed in flow 2.

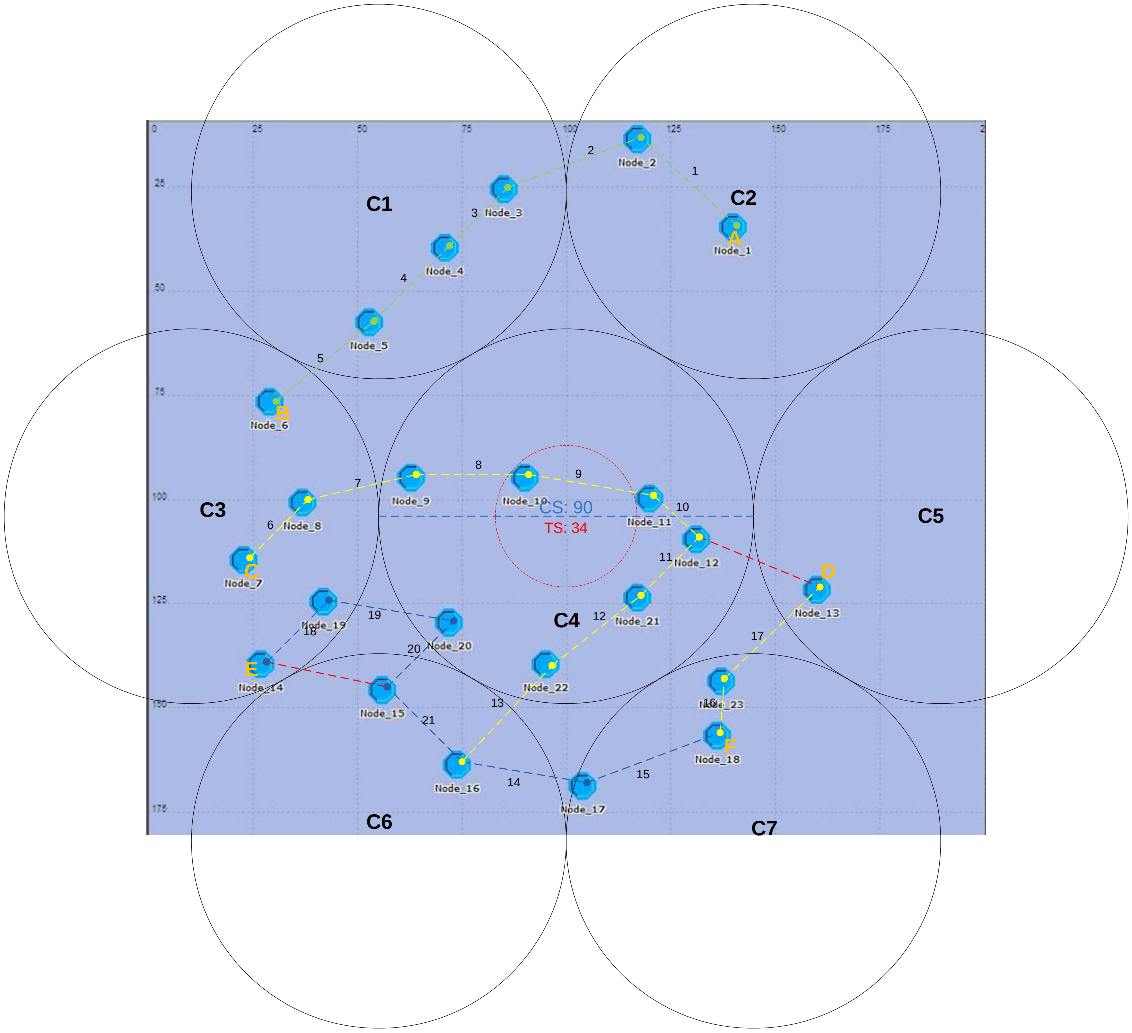
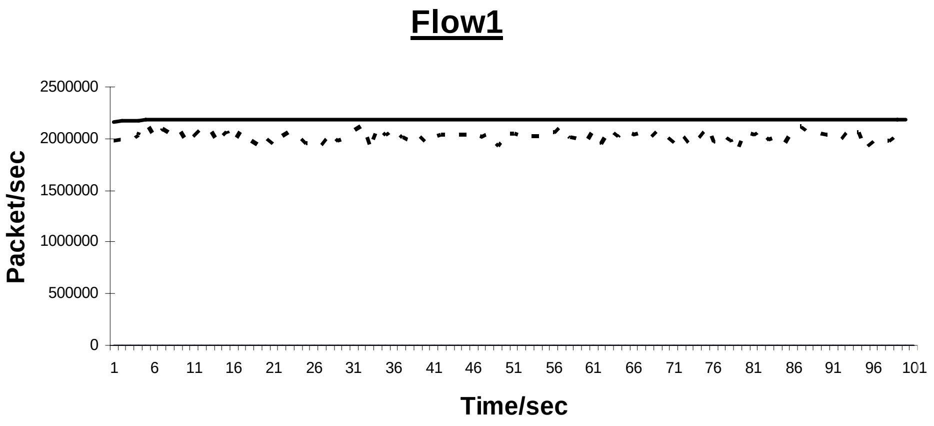
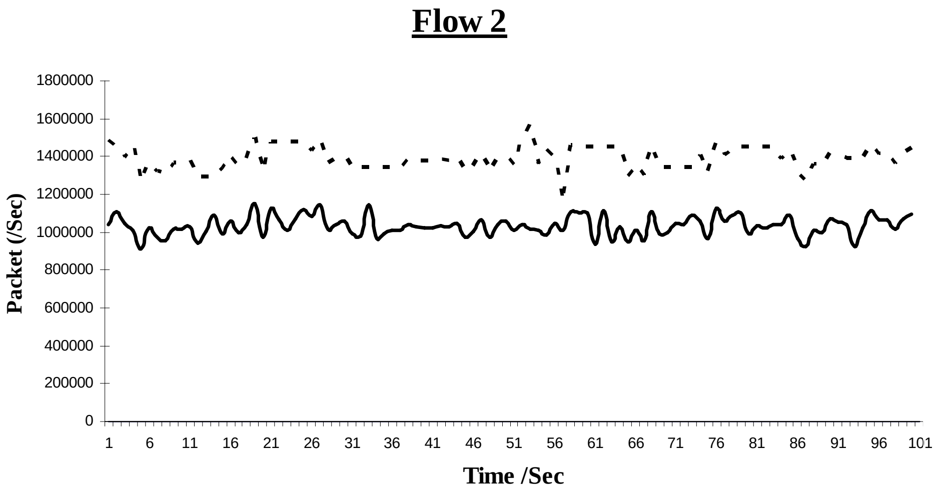


Fig 4.5: End-to-end Flows in OPNET

4.2.2.1 Results and Discussion

The simulation results for the three flows are shown in the following diagram (fig 4.6). There is the improvement in network performance in flow 1 and flow 3 of almost 8%, but in flow 2 the performance degrades by applying the proposed channel assignment scheme.





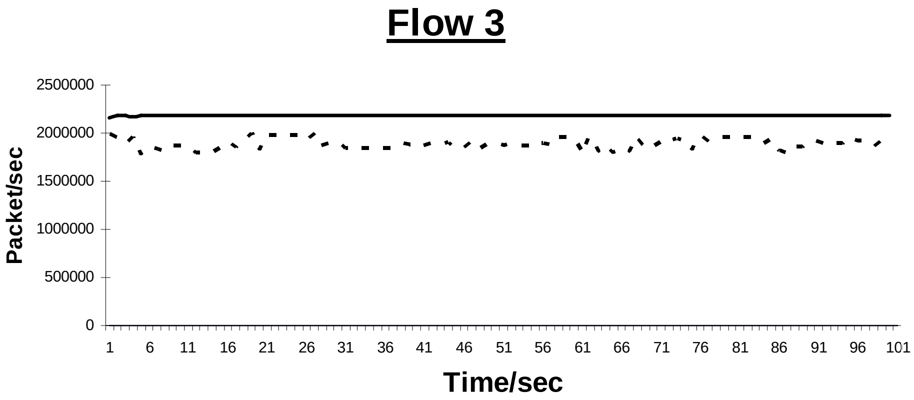


Fig 4.6: Network Performance in End-to-end flows

This is the trade-off between the non-coordinated interference avoidance and no of hops. In flow 2 to avoid the actual path we have to incorporate 7 additional hops to complete the end-to-end flow, which drastically affects the overall throughput of that flow. No of hops are also added in flow 3 but they are in some reasonable range.

Chapter 05

Conclusion and Future Work

5.1 Conclusion

Wireless Mesh Networks (WMNs) offers low-cost, reliable broadband wireless network access due to less dependence on the wired infrastructure. To develop the necessary protocols for mesh deployments numerous efforts have been made such that these deployments can fulfill the traffic demand of end users. Due to the affect of interference in a multi-path environment these efforts are not getting the optimal throughput particularly in conditions where the network flows are saturated.

The interference in WMN is classified into two broad categories; coordinated and non-coordinated. Among both of them the non-coordinated severely degrades the overall performance of WMN. We have studied in detail all aspects of non-coordinated interference and observed that in Far-hidden type of non-coordinated interference is exactly the opposite of Information asymmetric type, it means elimination of one type can automatically eliminate the other. Non-directional channel assignment is possible and can achieve better results as compared to unidirectional channel assignment.

For the minimization of non-coordinated interference a cluster based approach has been proposed for assigning channels to the links known as CCAS algorithm. CCAS classified the links into inter-cluster and intra-cluster links. In our research we have find out the exact no of interfering links for all inter-cluster links and also discovered the interfering area where the nodes reside acting as either sender or receiver of the interfering links. We have also determined the probability of finding a node in a particular interfering area.

On the basis of comments which we have made in our research a channel assignment scheme is proposed and simulated a WMN according to this. According to the simulation results, it has been observed that the proposed channel assignment scheme can eliminate the non-coordinated interference and can improve the overall throughput of the network provided the no of hops incorporated in case of path diversion are in some shorter range. In case of longer paths as a result of applying the proposed scheme, there is a possibility of degradation in network throughput of that flow.

5.2 Future Work

Future work is obviously in developing a channel assignment scheme for inter-cluster links such that they are not more dependent on the no of hops when the flow path diverts from the actual one. It may be some other way of assigning channels to inter-cluster links such that the non-coordinated interference has been minimized to enhance the overall throughput of the network.

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