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MAX FLOW BASED ON TOPOLOGY CONTROL CHANNEL ASSIGNMENT IN MULTI-RADIO MULTI-CHANNEL WIRELESS MESH NETWORKS

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ABSTRACT

The wireless network technologies have been popping up everywhere and becoming more popular day by day. Wireless Mesh Network (WMN) is one of the promising wireless technologies that provide effective, innovative and multihop solutions to provide the Internet connectivity to a large number of mesh routers with a low cost of construction. The interference problem between wireless links is critical and challenging problem faced in wireless networks that affects overall throughput. Hence, interference problem can be mitigated through efficient utilization of non-overlapping channels. Moreover, the multiple radios that are installed in each mesh router which operates in distinct channels enables the mesh routers to transmit packets simultaneously, resulting in increased throughput of the network. In this paper, we propose a novel algorithm Max-flow based on Topology-control Channel Assignment (MTCA) that aims to reduce the interference problem between the wireless links and maintaining on network connectivity. Simulation results reveal improved performance of the proposed algorithm in terms of mitigating interference problem and overall throughput of network as compared to existing work.

Keywords: *Wireless Mesh Network, Channel Assignment, Interference, Multi-Channel Multi-Radio, Throughput*

1. INTRODUCTION

Recently, the wireless mesh networks (WMN) have gained considerable attention due to their flexibility in building the multi-hop wireless access networks, solution for high capacity internet access and low-cost deployment [1, 2]. In addition, WMNs has the ability to integrate with various existing network technologies such as Wireless Sensor Networks (WSNs), cellular, Wireless-Fidelity (Wi-Fi) and Worldwide Interoperability for Microwave Access (WiMax) [2-4]. This feature of combined networks helps to enhance the communication reliability and increasing the coverage range of the given areas. The WMNs is usually consist of Mesh Clients Set (MCS), Mesh Routers Set (MRS) and Mesh Gateways Set (MGS) [5, 6] as shown in the Fig.1. The mesh clients set (MCS) represents the end user devices such as laptops, cell phones and other wireless devices (to name a few). In IEEE 802.11s standard, each MCS has only one interface for connecting through the frequency spectrum [7]. The mesh routers set (MRS) act as the backbone of the network topology. MRS has ability to connect the mesh clients set with the mesh gateways set through multi-hop environment. Furthermore, the mesh router supports the simultaneous transmission to increase the capacity of the network[8] because each mesh router is equipped with multi-interface to connect with multi-channels in the network topology [9].The radio interfaces of the two routers can communicate with each other if they have common channel between them and are located within the transmission range of each other. The mobility of the mesh routers is extremely limited as compared to mesh clients set. Some of these mesh routers act as a mesh gateways set (MGS) to connect the local network with internet via wired connection.

In WMNs, the IEEE 802.11b/g and IEEE 802.11a standards have capability to support the environment of the wireless networks having three and twelve non-overlapping channels in the 2.4GHz and 5.0GHz band respectively [10-12]. Therefore, the aforementioned limitation of the non-overlapping channels increases the probability of interference problem between the adjacent links in the multi-hop wireless networks.

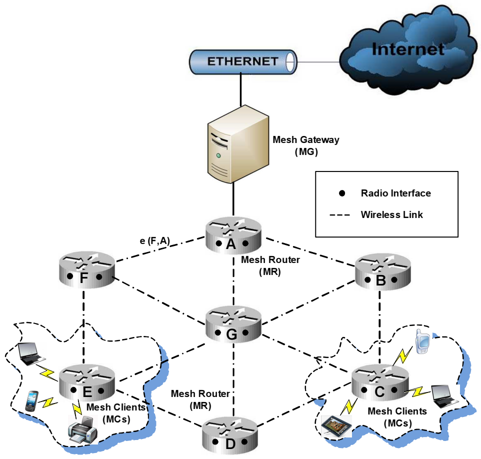

Fig1: Architecture Of Physical Topology Of Wireless Mesh Network

The interference problem is the critical factor in reducing the throughput of the wireless mesh network [13]. In the literature, the interference aware channel assignment schemes in multi-radio multi channels are developed to enhance the throughput of the wireless network through mitigating the interference problem while maintaining on the network connectivity [14]. Equitable distribution of non-overlapping channels between the wireless links helps to reduce the impact of interference problem in a given network topology.

In this paper, a novel algorithm called Max-flow based on Topology-control Channel Assignment (MTCA) is proposed for interference channel assignment. The proposed MTCA algorithm aims to utilize all the available non-overlapping channels effectively to improve the network capacity. As the result, the MTCA selects a set of links to be used out of all wireless links to maximize the overall network capacity.

Moreover, the proposed MTCA algorithm is to remove the useless links from the original network topology with a guarantee that the alternative paths between all the nodes exist to maintain the network connectivity. The MTCA uses the number of neighbors and the Euclidean distance from the gateway as metrics to distinguish the wireless links. Moreover, the MTCA formulate a new function named as Function Selection Channel (FSC) to select a channel for each link in the network topology. The FSC selects a channel for each link based on the radio status of the two nodes which constitutes the target link. In this paper, the proposed channel assignment process is based on the behavior of CSMA/CA MAC protocol. It is worth mentioning that, MTCA removes the useless links from the original topology by unassigned a common channel between the two nodes constituted the target link. The rest of this paper is organized as follows: Section 2 describes the related work in pursuit of interference aware channel assignment schemes. Section 3 illustrates the system model and problem formulation. The design of proposed centralized channel assignment algorithm is presented in Section 4. Section 5 presents the performance evaluation of MTCA and experimental results. Finally, Section 6 concludes the paper.

2. RELATED WORK

The interference aware channel assignment algorithms are developed to enhance the throughput of the WMNs through mitigating the interference problem. In designing of the interference aware channel assignment schemes, channel distribution and link quality are used as metric to measure the level of interference[15]. The limitation on the number of the non-overlapping channels and number of the radio interfaces that are installed on each node makes the channel assignment design is extraordinarily complicated and proved to be NP-hard [13, 16]. In the literature, the existing channel assignment schemes are classified into different categories. First, channel assignment based on available knowledge of network topology, are classified into Centralized and Distributed channel assignment schemes [17]. Second, channel assignment based on channels frequency, are classified into Fixed/Static, Dynamic and Hybrid Channel Assignment schemes [18].

The interference aware channel assignment scheme proposed in [19], based on the dynamic and centralized channel assignment approaches called as Breadth First Search Channel Assignment (BFS-CA). In this scheme, the authors utilize Expected Transmission Time (ETT) proposed by [20] as metric for the link quality. Moreover, the Conflict Graph (CG) that was proposed by [21] is extended to Multi Conflict Graph (MCG) to cover all the radio interfaces within each node. The MCG is used to represent and capture the impact of the interference present between the wireless links in a network topology. BFS-CA uses the output of the MCG as input in the proposed channel assignment process. In Common Channel Assignment (CCA) scheme [20], the fixed number of radio interfaces on each node are assigned with the same number of channels. The first radio interface on each node is assigned to first channel; second radio interface assigned to second channel and so on. The network connectivity in the CCA is guaranteed. However, the channel assignment process in CCA in terms of reducing the effect of interference between the wireless links is incompetent. The throughput would be optimal in the CCA, when the number of radio interfaces in each nodes increase to assign many channels. The proposed interference aware channel assignment scheme in [22] is based on the centralized channel assignment approaches called as Tabu-based Algorithm (CTA). In this scheme, the concept of the conflict graph is used to assigning the channels between the links in the network. The major objective of this algorithm is to mitigate the network interference problem while maintains on the constraints of the network connectivity. In the network topology, the constraint of the network connectivity ensures the multiple paths still exist between all the nodes after channel assignment. In [23]the proposed algorithm is based on the centralized channel assignment approaches called as Connected Low Interference Channel Assignment (CLICA). CLICA used the concept of topology preservation and topology control based on traffic independent in designing the channel assignment process. The main target of the CLICA is constructed network topology with low interference while preserving the network connectivity. In this scheme, the network topology is represented by the graph. CLICA gives all the nodes in the network topology a weight based on constructing the shortest path and the number of free radios interface. In this scheme the channel assignment priority gives to a node has only a single radio interface is unassigned. In the work presented by [15] proposed a new channel assignment algorithm to mitigating the interference problem in the network topology through high performance links. The proposed algorithm in this work is centralized channel assignment known as Utility Based Channel Assignment (UBCA). The topology graph is used to formulate the network topology and the conflict graph also is used to formulate the interference between the wireless links. UBCA gives each link in the network topology a weight equal the probability of packet delivery without considering the specific traffic pattern. In the work presented by [24] the authors proposed three algorithms for interference-aware channel-assignment named TICA, e-TICA, and e-TICA2. These algorithms aims to reduce the interference problem between the wireless links, increase the throughput of the network and guarantee the network is connected. In this work, topology control with the concept of power control is used in designing the proposed channel assignment algorithm. In the work presented by [25], the proposed algorithm improved the genetic algorithm NSGA-II to enhance the throughput of the network and reducing the interference while maintaining a maximum number of links between the nodes. In this work, the proposed interference aware channel assignment algorithm is formulated as topology control using the formulation of genetic algorithm. This algorithm aims to choose the number of links among all the links in the network topology to assign the channels without affecting on the efficiency of the network. In another attempt, the authors in [26] proposed non-overlapping channel assignment algorithm named as DPSO-CA based on topology preservation as explained by [27]. The DPSO-CA aims to balance between the maintaining the network connectivity and mitigated the co-channel interference based on organizing the mesh nodes with available channels. Moreover, the conflict graph model has been used to capture the interference problem between the wireless links in the network topology. In DPSO-CA supposes all nodes in the network topology have the same number of radios which are assigned the conformable set of channels to maximize the network connectivity.

3. MODEL AND PROBLEM FORMULATION

In this section, the system model and the formulation of the channel assignment problem in multi-radio multi-channel WMNs, are discussed in detail.

3.1. Network Model

Generally, the physical topology of WMN is designed as an undirected graph $\mathrm{G_t} = (\mathrm{V_t}, \mathrm{E_t})$ as shown in Fig.2. Where $\mathrm{V_t}$ is the set of nodes in the $\mathrm{G_t}$ and is represented as $\mathrm{V_t} = \{\mathrm{v_1}, \mathrm{v_2}, \dots, \mathrm{v_N}\}$. All the nodes in $\mathrm{G_t}$ has a specific number of interfaces (multi-radios) such as $f_i(v) \geq 1$ (where i is interface number of the node$v, \forall v \in V_t$). E_t is the set of undirected links (edges) between the nodes in $\mathrm{G_t}$ which is represented as $E_t = \{l_{(v_1,v_2)}, l_{(v_2,v_3)}, \dots, l_{(v_i,v_j)})\}$. In the given network topology $\mathrm{G_t}$, the link $l_{(u,v)}$ is exist between each two nodes, when the Euclidean distances d between them is less than or equal the transmission ranges of each other ($d(u,v) \leq T_R$). Suppose the interference range IN_R for each node is two times greater than the transmission range T_R ($IN_R=2\times T_R$). The radio interfaces in each two adjacent nodes in $\mathrm{G_t}$ are operating on a common channel. The number of non-overlapping channels available in the network are denoted as $CH = \{ch_1, ch_2, \ldots, ch_n\}$. MTCA assume that each wireless link should be assigned exactly one channel due to a limited number of non-overlapping wireless channels in IEEE 802.11 Standard. Furthermore, the number of the channels that should be assigned to each node v_i must not exceed the number of radio interfaces that is equipped with that node ($CA(v_i) \leq f_i$).

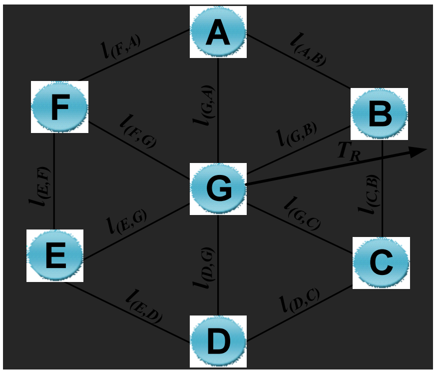

Fig 2: Undirected topology graph of wireless mesh network

3.1.1. INTERFERENCE MODELS

Interference is one of the main problems faced by the communication channels in the wireless networks. The interference problem is affecting in both sides of the receiving and sending nodes. In WMNs, the quantifying of the interference and the behavior of the medium access control (MAC) are essential components in the design and deployment of multi-radio multi-channel. Hence, they have a direct effect on the throughput of the wireless network. Thus, impact of interference between the wireless links and the behavior of the MAC protocols has been modeled extensively in existing literature. The most of existing design and deployment of wireless mesh networks are based on the Physical model, Protocol model and Extended Protocol model of interference [14, 16].

In Physical Model, the transmission between any two nodes (N_i and N_j) to be successful without collision when, the Signal Strength (SS_{ij}) of sender node is strong enough to send the packets to the receiver and the Noise Ratio (NR_j) at the receiver node is above from a certain threshold, such as $SS_{ij}/NR_j >= \text{SNR}_{\text{thresh}}$. Where SS_{ij} is represents the signal strength at the sender node (N_i), NR_j is the total noise at the receiver node (N_j), and SNR_{thresh} is the threshold of signal to noise ratio[14].

In the Protocol Model, the data transmission between two nodes (A and B) to be successful without collision between the data packet when, no other sender (node C) located within the carrier sensing range of the receiver (node B) is transmitting the data simultaneously during the time of data transmission [14]. On the other hand, if a sender (A) needs to send the data to receiver (B), the transmission is successful without interference if the following conditions are satisfied:

I. Euclidean distance between the sender and receiver (A and B) less than or equal to transmission range$d(A, B) \leq T_R$.

II. No other sender node $\boldsymbol{C}$ located within the carrier sensing range of B send packets to receiver node B during the time of data transmission using the same channel between A and B.

The Extended protocol model of interference is defined by [16] to capture the impact of interference between the wireless links. This model is based on the Euclidean distance d between two adjacent nodes (sender-receiver pair) in the network topology. The two links $l_{(u1,v1)}$ and $l_{(u2,v2)}$ are interfering they use a common channel and the distances between them (sender-receiver pair) is bigger than the transmission range of each other, such as

$$d(u_1, u_2),\ d(u_1, v_2),\ d(u_2, v_1),\ d(v_1, v_2) > T_R.$$

Most of the existing works in literature uses the concept of the conflict graph as defined in [21] to model the interference problem between wireless links. In the conflict graph, $G_f = (V_f, E_f)$ all the links in network topology G_t represented as corresponding vertex. There is an edge between two vertices on the conflict graph $\mathrm{G_f}$ if the corresponding links in the network topology $\mathrm{G_t}$ interfere with each other [28]. In the conflict graph, we use the terms “vertex” and “edge” instead of “node” and “link” as in the network topology graph [29].

Definition 1 (Conflict Graph). A conflict graph $G_f = (V_f, E_f)$ is conduced by $G_t = (V_t, E_t)$ with $V_f = E_t$ and $(l_{(u1,v1)}, l_{(u2,v2)}) \in \mathrm{E_f}$ if $l_{(u2,v2)}$ interfere with link of $l_{(u1,v1)}$ in G_t.

In this paper, the topology graph has been used to model the network topology while extended protocol model and conflict graph has been used to capture the effect of interference problem between the wireless links.

Algorithm 1. MTCA (G_t , G_f , H_i , CH)

```
Input:
        $G_t = (V, E)$: The topology graph
        $G_f$: The conflict graph of $G_t$
        $H_i = (h_1, h_2, \dots, h_N)$ : number of hop
        CH: The set of available channels
        $f_i(v)$: Number of interface i in each node v

Require:
        CH > 0
        $f_i \leq$ CH
Channel Assignment:
for each number of hop $H_i = (h_1, h_2, \dots, h_N)$ do
  set a weight to each link in hop $H_i$
  Order all the links base on has weight descending
  for all links $l_{(u,v)}$ within the $H_i$ do
    if the two nodes (v, u) constitutes the target link $l_{(u,v)}$ does not have
      a common node (x) within the NNs of each other
        $l_{(u,v)} \leftarrow$ Least. Interference.Channel ($l_{(u,v)}$, CH)
    else if ( ($l_{(u,x)} \leftarrow ch_i$) & ($l_{(v,x)} \leftarrow ch_i$) )
            if the two nodes (v, u) constitutes the target link $l_{(u,v)}$ have
          another a common node (x1) within the NNs of each other
          else if ( ($l_{(u,x1)} \leftarrow ch_i$) & ($l_{(v,x1)} \leftarrow ch_i$) )
                $l_{(u,v)} \leftarrow$ removed from the new topology $G_t^{`}$
                  else
                  $l_{(u,v)} \leftarrow$ Least. Interference.Channel ($l_{(u,v)}$, CH)
                  end if
             else
           $l_{(u,v)} \leftarrow$ Least. Interference.Channel ($l_{(u,v)}$, CH)
             end if
        else
          $l_{(u,v)} \leftarrow$ Least. Interference.Channel ($l_{(u,v)}$, CH)
      end if
    end if
  end for
end for
```

3.2. Problem Formulation

In WMNs, the optimal distribution of the non-overlapping channels between the wireless links contributes in simultaneous communication between the adjacent wireless links. However, the unfair distribution channels between the interfering links may cause high level of interference in the network. Furthermore, the numbers of the non-overlapping channels available in the IEEE 802.11 standard are limited. Subsequently, the channel assignment algorithm proposed in this paper aims to utilize and distribute the non-overlapping channels effectively between the wireless links to reduce the impact of interference in network topology. As a result, the interference problem between the wireless links in MTCA is mitigated while maintaining the network connectivity. Therefore, to utilize the available non-overlapping channels effectively, the proposed algorithm MTCA considered some constraints that are formulated as follows:

i. The number of radio interfaces installed on each node should always be less than or equal the number of the non-overlapping channels available on the network environment, as defined in Equation (1).

$$\sum_{f_i \in u}^{u \in V_t} f_i(u) \le CH_i \qquad (1)$$

$$f_i \in u; u \in V_t$$

Where $f_i(u)$ represents the number of interfaces on the node$u, \forall u \in V_t$, and CH_i represents the non-overlapping channels denoted by $ch_1, ch_2, \dots, ch_n$.

ii. The total number of channels that will be assigned to the incident links of a node u must be less than or equal the number of interfaces installed on that node. As defined in Equation (2).

$$\sum_{l_{(u,v_i)} \in E_t}^{ch \in CH} CA\left(l_{(u,v_i)}, ch\right) \le \sum_{f_i \in u}^{u \in V_t} f_i(u) \qquad (2)$$

$$\forall u, v \in V_t; \forall l_{(u,v_i)} \in E_t; \forall ch \in CH; \forall f_i \in u$$

4. THE PROPOSED MTCA ALGORITHM

This section introduces a novel multi-radio multi-channel algorithm called Max-flow based on Topology-control Channel Assignment (MTCA) which is static and centralize in nature. The MTCA effectively utilizes all the available non-overlapping channels, to improve the network capacity, by selecting the high performance links from the available links in the network topology. Moreover, the proposed algorithm guarantees the multi-paths, between the two nodes in the network topology, that exist in the new network topology after the process of channel assignment to maintain the network connectivity. The proposed MTCA algorithm has two phases.

The first phase of the MTCA is the link scheduling as presented in Algorithm 1. In this phase, the MTCA visits all the links in each group (from *1-hop* to *N-hop)* based on their priority order. The MTCA uses the FSC to select the least interference channel for the visiting links within each group. The FSC selects a channel for each link based on the radio status of the two nodes that constitutes a link. For each link in a given network topology, the MTCA checks the list of the Neighboring Nodes (NNs) for the two nodes that constitutes the target link. The NNS contains all the adjacent nodes for each of the two nodes that constitute the target link. If the two nodes that constitute the target link do not have common nodes within the NNs of each other, the MTCA selects a channel to the target link based on the FSC. Otherwise, if the two nodes constitute the target link have common nodes within the NNs of each other. This means there are wireless links located within the carrier sensing range of the target link based on the extended protocol model of interference. Accordingly, the MTCA checks the channel assignment cases of the wireless links between the common nodes and the two nodes which constitute the target link. If the channels are not assigned to links between the common node and the two nodes constitutes the target, then the MTCA selects a channel to the target link according to the FSC. If all the links between the common node and the two nodes constitute the target link are assigned channels, then the MTCA checks another neighboring node in the NNs of the two nodes that constitute the target link rather than the common node to ensure there is more than one path in the network topology rather than the target link. In the case there is another neighbor node for each of two nodes that constitute the target link and the links between the common node and the two nodes that constitute the target link are assigned channels, then the MTCA considers the target link as useless link and remove it from the new topology $\tilde{G}_t$ as illustrated in the following example. Otherwise, the MTCA selects a channel to the target link based on the FSC.

For example, suppose that a given network topology consisting of five wireless nodes A, B, C, D and E as shown in Fig.3. The wireless link between the two nodes exists, when they are located within the transmission range of each other. The MTCA considers that the link $l_{(A, B)}$ between the two nodes A and B is a useless link according to the following conditions. The first condition is when the two nodes constitute the target link $l_{(A, B)}$ has a common node C in their NNs. Moreover, the wireless links between the common node and the two ends of the target link (A and B) are assigned channels ch_1 and ch_2. The second condition is when the two nodes constitute the target link $l_{(A, B)}$ has a neighbor node in the NNS rather than the common node. Moreover, the links between the two nodes constitute the target link $l_{(A, B)}$ and its neighbors are assigned channels such as $l_{(A, B)} = ch_3$ and $l_{(B, E)} = ch_4$

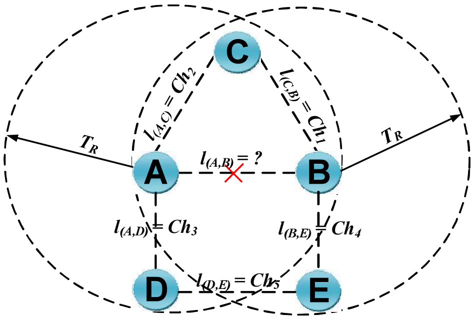

Fig 3: The network topology of WMN

As mentioned in the previous example, the MTCA considers the link as useless after ensuring the given network topology has more than one alternative path.

4.1. The Priority Of The Wireless Links

Usually, the data traffic flows in the wireless mesh network is from/to the mesh gateway. Thus, unfair distribution of the channels between the links close to the gateway may cause the problems of bottleneck links and data collisions in the network which degrade the overall performance of the network. Therefore, the designing of the channel assignment process in the MTCA aims to reduce the problems of the data collisions between the nodes and bottleneck links between the links close to the gateway. However, the MTCA considers that the data traffic between the wireless links is uniform throughout the network. Therefore, it is very difficult to assign the non-overlapping channels between the wireless links without considering the traffic flows in the network topology. As a result, the MTCA used the geometric location of each link in the network topology to estimate the links quality. Therefore, all the links in the network topology are divided into groups based on the number of hops far from the gateway.

In the MTCA, the priority is given to links close to the mesh gateway. Further, to distinguish between the links in the same group, the MTCA uses Euclidean metric to compute the distance between the links as defined inEquation.3.

$$D = \sqrt{(u_1 - u_0)^2 + (v_1 - v_0)^2} \qquad (3)$$

The MTCA gives the priority to a link which constructs the shortest path between the links in the same group. This is because, the success of sending packets depends on the length of the wireless link between nodes. Hence, the rate of the process of sending and receiving packets be high whenever the distance between nodes is decreased.

In the MTCA, all the links that are close to or emerges from the gateway are classified as high performance links because, most of the data traffic in the network topology is from/to the gateway. Therefore, MTCA gives each link within each group a weight $W\big(l_{(u,v)}\big)$ equals the total number of the neighbors of the two nodes which constitute the link as defined in Equation.4.

$$W\big(l_{(u,v)}\big) = \sum_{u,v\in N}^{N} \big(N(u) + N(v)\big) - 2 \qquad (4)$$

Where $W\big(l_{(u,v)}\big)$ is the weight for the link$l_{(u,v)}$ of a node u in each group. $N(u)$ and $N(v)$ are the number of neighboring nodes for node u and v respectively that constitutes the link $l_{(u,v)}$. (-2) used to exclude the two endpoint nodes of the target link from the result of the summation.

As a result, MTCA gives the priority to a link which connects between several nodes to construct a high quality path between the gateway and other nodes within the network topology.

4.2. The Function Selection Channel (FSC)

The FSC tries to find as much as possible the LIC to mitigate the impact of interference between the wireless links. The steps of the proposed FSC are presented in Algorithm 2. The LIC is not used much by the links located within the interference range of the two nodes that constitute the target link. According to the conflict graph model (G_f), the MTCA defines all the channels used by the wireless links that potentially interfere with the target link $l_{(u,v)}$ as $PICh\big(l_{(u,v)}\big)$ byEquation.5.

$$PICh\big(l_{(u,v)}\big) = \sum_{u,v\in V_f}^{c\in C} \tilde{l}_{(u,v)}(ch) \qquad (5)$$

Where $\tilde{l}_{(u,v)}$ represents the links that potentially interfere with the target link $l_{(u,v)}$. And ch represents the channels assigned to the links that potentially interfere with the target link $l_{(u,v)}$.

The FSC gives all the channels in PICh($l_{(u,v)}$) a weight based on the number of times used by the links that potentially interfere with the target link. The main target of the PICh is to mitigate the collisions between the wireless links in the given network topology. The FSC determines the Available Channel Set (ACS) for all the links within each group. The ACS contains all the channels that can be assigned to the target link based on the radios status of the two nodes that constitute the link.

Moreover, the channels in the ACS are given weights based on the number of times that have been used in the overall network topology. To assign the LIC for each link, the FSC checks the radios status of the two nodes that constitute the target link. There are two cases related to the radio status which are stated next.

In the first case of the radio status when the two nodes formed a link have free radios, then in this case, the ACS contains all the available channels in the IEEE 802.11 package. Then, the FSC gives all the channels in ACS a weight based on the number of times used in the overall network topology.

Algorithm 2. FSC ($l_{(u,v)}$, ch, G_f)

Input:

$l_{(u,v)}$: The link between nodes u and v.
ch: Available channels set.
G_f : The conflict graph.

Output:

ch: Least Interference Channel.

```
$I.Link_i$ ← Number of the links in $G_f$ for a link $l_{(u,v)}$.
$PICh(l_{(u,v)})$ ← All the channels used by the links that potentially
                    interfere with the target link $l_{(u,v)}$.
$ACS(l_{(u,v)})$ ← All the channels that can be assigned to the target link $l_{(u,v)}$.
for ($ch_i \in CH$) do
  if the two nodes $(u,v)$ formed the link $l_{(u,v)}$ have free radios
     $ACS(l_{(u,v)})$ ← Contains all the channels in the IEEE 802.11 package.
    if $(ACS(l_{(u,v)})) - (PICh(l_{(u,v)})) \leq 0$
      ch ← min rank in $\{PICh(l_{(u,v)})\}$ for channels in $\{ACS(l_{(u,v)})\}$
    else
      MinCh ← $\left(ACS(l_{(u,v)})\right) - (PICh(l_{(u,v)}))$
      ch ← min rank in $\left\{ACS(l_{(u,v)})\right\}$ for channels in $\{MinCh\}$
    end if
  else (only one node from the two nodes $(u,v)$ formed the link $l_{(u,v)}$ have free radios)
     $ACS(l_{(u,v)})$ ← Contains just the channel assigned to incident links
                    of a node which has no free radio.
     if there are channels assigned to links between the common node and
       the two ends nodes of the target link $l_{(u,v)}$.
       CCL ← Contains all the channels assigned to links between a common node and $(u, v_i)$.
      if $(ACS(l_{(u,v)})) \cap (CCL(l_{(u,v)})) \neq 0$
        MinCh ← $(ACS(l_{(u,v)})) \cap (CCL(l_{(u,v)}))$
        ch ← min rank in $\left\{CCL(l_{(u,v)})\right\}$ for the channels in $\{MinCh\}$
      else if $(ACS(l_{(u,v)})) - (PICh(l_{(u,v)})) \leq 0$
           ch ← min rank in $\{PICh(l_{(u,v)})\}$ for the channels in $\{ACS(l_{(u,v)})\}$
        else
           MinCh ← $(ACS(l_{(u,v)})) - (PICh(l_{(u,v)}))$
           ch ← min rank in $\left\{ACS(l_{(u,v)})\right\}$ for the channels in $\{MinCh\}$
        end if
       end if
    end if
  end if
end for
return ch
```

The aim of the ACS is to guarantee that the channels are distributed equitably between the links in a given topology. Hence, the FSC has two possibilities to select the LIC to the target link which are stated next.

In the first possibility some channels in the ACS do not exist in the PICh which means there are some channels that are not used by the links that potentially interfere with the target link. Thus, the FSC selects the candidate channel from the ACS based on the least weight.

For example, suppose the potential interference links for a link l_1 are l_5, l_6, l_7, l_8, l_9, l_{10}, l_{11}, l_{12} and l_{13} and the non-overlapping channels are assigned to them such as ch_1, ch_3, ch_2, ch_1, ch_1, ch_2, ch_3, ch_3 and ch_1 respectively. Thus, the PICh contains all the channels assigned to the wireless links that potentially interfere with the link l_1. The channels in the PICh are arranged based on the number of times used by these links as shown in Table.1.

Table 1: The list of channels in PICh

Channel	ch_1	ch_2	ch_3
Weight	4	2	3

On the other hand, suppose the ACS contains the channels ch_1, ch_2, ch_3, ch_4 and ch_5 that are arranged based on the number of times used in the network topology as shown in Table.2.

Table 2: The list of channels in ACS

Channel	ch_1	ch_2	ch_3	ch_4	ch_5
Weight	14	11	7	10	5

According to the FSC, the LIC of the link l_1 is channel ch_5 due to the fact that channel ch_5 is not used by the potential interference links. Moreover, the ch5 is used less number of times in the network topology as compared to the existing channels. As observed, the MTCA aims to increase the simultaneous transmission between the links by selecting a channel outside the PICh (channels used by the links which potentially interfere with the target link l_1).

In the second possibility, when all the channels in the ACS exist in the PICh then, all the candidate channels are used by the links which may interfere with the target link. In this case, the candidate channel is selected from the ACS based on the least weight from the PICh. From the previous example, suppose the ACS contains the channels ch_1, ch_2 and ch_3 with the weights 10, 24 and 30 respectively. Thus, the FLIC selects channel ch_2 for the link l_1 due to the less usage of the ch_2 between the links that potentially interfere with the link l_1 as illustrated in Table 1. The observations from example shows that the MTCA aims to mitigate the impact of interference problem by the LIC from the PICh. The PICh contains all the channels that are assigned by the links that potentially interfere with the target link.

In the second case of the radio status, when only one node, from the two nodes that constitute the target link, has free radio interfaces then the ACS contains just the channel assigned to node which has no free radio interfaces. Then, the FSC has two possibilities to select the least interference channel to the target link.

In the first possibility, when there are channels assigned to links between the common node and the two end nodes of the target link then the FLIC selects the LIC for the target link from both CCL and ACS. The CCL contains all the channels assigned to links between the common node and the two end nodes of the target link. The FLIC gives all the channels in the CCL a weight based on the number of times used by the links that potentially interfere with the target link. In the case when there are common channels between CCL and ACS, the LIC is selected from these common channels based on the least weight in the CCL. In the case when there are no common channels between the CCL and ACS, then the LIC is selected based on two possibilities. Firstly, in the case when there are channels in the ACS that do not exist in the PICh then, the LIC is selected based on the least weight from the ACS. Secondly, when all the channels in the list of ACS exist in the PICh then, the LIC is selected from the ACS based on the least weight from the PICh.

In the second possibility when the two ends of the target link do not have channels assigned to links between the common node and the two end nodes of the target link then, the FLIC selects the LIC based on two possibilities. If there are channels in the ACS that do not exist in the PICh then, the LIC is selected based on the least weight from the ACS. If all the channels in ACS exist in the PICh then, the LIC is selected from the ACS based on the least weight from the PICh.

5. EVALUATION AND EXPERIMENTAL RESULTS

The The simulation model uses the NS-2.32 simulator to evaluate and analyze the experimental results of the network throughput, while the numerical model uses MATLAB (2012b) to verify and analyze the assumptions of the proposed algorithms for network capacity and the fractional network interference. The performance of proposed algorithm is compared with the relevant channel assignment schemes available in literature such as Common Channel Assignment (CCA) [20] and the Connected Low interference Channel Assignment algorithm (CLICA) [23].

5.1. The Numerical Results

In the numerical model the MATLAB (2012b) is used to verify and analyze the assumptions of the proposed MTCA algorithm for the network capacity and the network interference. Furthermore, in these experiments, the routing protocol and mesh gateway of the network topology are not considered. Two numerical metrics of Fractional Network Interference (FNI) and Network Capacity (NC) are used to verify the performance of the proposed F-NOC algorithm by using the MATLAB (2012b). Moreover, the FNI and NC are used to measure and evaluate the effect of the interference between the wireless links and the network capacity of the network topology.

The Fractional Network Interference (FNI) is defined as the ratio of total number of interference to the overall potential interference number in the network, which can be used to measure the final interference after the channel assignment [26, 30-32].

The Network Capacity (NC) is defined as the maximum number of concurrent transmissions in the network topology, which can be calculated by computing the maximum independent set in the conflict graph [15, 23].

In these experiments, different number of nodes, 10, 20, 30, 40 and 50, are generated randomly within the area of 1000m ×1000m to analyze the impact of interference between the wireless links with an increased number of nodes. The transmission and interference ranges are 250m and 500 m, respectively.

Fig.4 shows the average capacity of the given network achieved by the algorithms MTCA and CLICA and CCA. The MTCA and CLICA outperforms the CCA due to efficient utilization of all non-overlapping channels available in IEEE 802.11a, while CCA just use three channels based on the number of radios in each node. It is also evident from the Fig.4 the network capacity achieved by the MTCA outperforms the TLCA and CLICA when the number of nodes is increased. The impact of interference between the links increased when the number of nodes increases. The network capacity in the MTCA is significantly higher as compared to the CLICA and CCA due to the impact of removing the useless links form the original network topology. Thus, the number of concurrent transmissions between the wireless links is increased by removing the useless links from the original topology.

Fig.5 shows the results of the fractional network interference for different random network topologies. As shown in Figure 5.6, the proposed MTCA algorithm has lower interference weight than the CLICA and CCA. The fractional network interference in the CLICA and CCA is significantly higher as compared to the MTCA due to the increased number of concurrent transmissions between the links. As a result, the efficient channel assignment for high performance links in the MTCA helps to reduce the impact of interference between the wireless links.

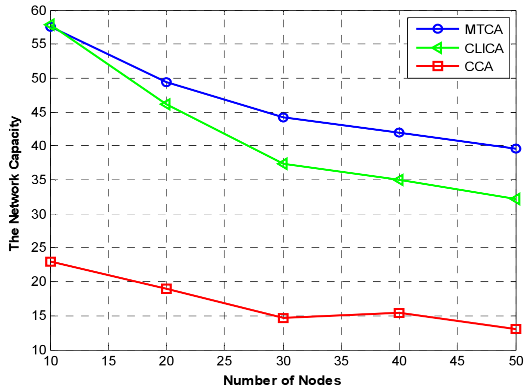

Fig 4: The network capacity

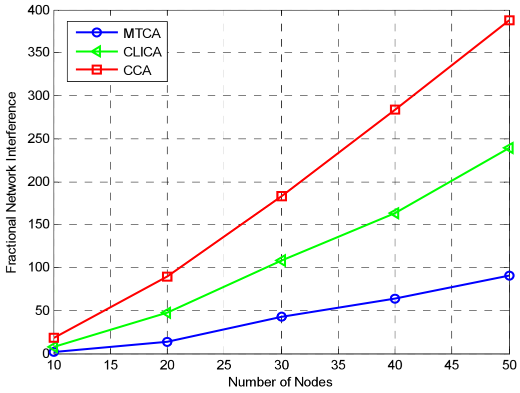

Fig 5: The Fractional Network Interference

5.2. The Simulation Results

To evaluate the performance of the TLCA, different experiments are performed using the simulator NS-2.32. The experiments are conducted with various traffic models. Table 3 summarizes the simulation parameters used in different experiments.

Table 3: The simulation parameters of NS-2

Number of nodes	50
Maximum number of radio interfaces per node	3
Terrain Dimensions for IEEE 802.11b\a radio	1000×1000m
Radio Propagation model	Two rays
Data rate IEEE 802.11a radio	54Mbps
Packet size (fixed)	512Bytes
Placement of nodes	Uniform Random
Non-overlapping channels in IEEE 802.11a	12 channels
Packet inter-arrival mean	0.33mSec

i. The Effect of End-to-End Throughput of Single Hop Flows

This experiment is conducted to evaluate the link layer performance of the proposed TLCA algorithm in terms of aggregate throughput of the single-hop traffic flows model. The single-hop traffic flows model helps to evaluate the network performance in case when all wireless links carry the same load. the non-overlapping channels of IEEE 802.11a are used in this experiment to measure and evaluate the effect of interference problem between the wireless links. In the given topology 5, 10, 20, 30, 40 and 50 single hop flows are initiated respectively using TCP traffic between randomly selected nodes. The experiments repeated 20 times for each traffic flows profile, and report the average of the throughput for each number of flows. Fig.6 shows that the result of the average throughput achieved by the three algorithms based on different numbers of flows. The average throughput achieved by the proposed MTCA algorithm outperforms the CLICA and CCA. The removal of the useless links from the original network topology in the MTCA helps to increase the simultaneous transmission between the links, which in turn increases the throughput of the MTCA as compared to the CLICA and CCA.

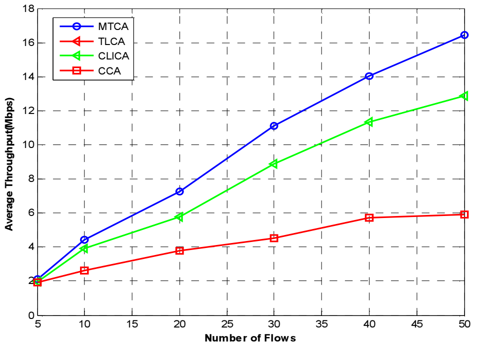

Fig 6: The average throughput of the network topology

ii. The Effect of Throughput in Different Number of Peer-to-Peer Traffic Profiles

In this experiment, two types of traffic profiles, named as gateway profile and random profile, are used to analyze and evaluate the effect of end-to-end throughput of the multi-hop traffic load in the WMN. The given network topology consists of 50 wireless nodes and the three radio interfaces are installed on each node. The IEEE 802.11a standard, with 12 non-overlapping channels, is used to evaluate and analyze the performance of the proposed and relevant algorithms when the number of traffic flows is increased.

In the gateway profile, the traffic flows in the network topology are conducted between the gateway and randomly selected nodes. The main target of this experiment is to verify the effect of interference between the wireless links close to the gateway. In this experiment 5, 10, 20, 30, 40 and 50 multi-hop traffic flows are generated between the gateway and randomly selected node. Fig.9 shows that the average throughput of the MTCA is higher as compared to the CLICA and CCA when the number of flows is increased in the network topology. The average throughput in the CLICA and CCA is relatively low as compared to the MTCA due to bottleneck problem that is generated between the links close to the gateway while operating on a limited number of channels. Moreover, the removal of the useless links from the original topology in the MTCA helps to assign varying channels between the wireless links close to the gateway.

In the random profile, the traffic flows in the network topology are generated between the random pairs of nodes. The main target of this experiment is to evaluate and analyze the impact of interference between the links in the proposed algorithm by comparing it with the relevant algorithms. The 5, 10, 20, 30, 40 and 50 multi-hop traffic flows are generated between randomly selected source-destination pairs to verify the optimal distribution of the channels between the links in different number of traffic load. Fig.10 shows the average end-to-end throughput of all generated flows for CCA, CLICA and MTCA. The simulation result shows that MTCA provides a significant improvement in the average throughput as compared to the CLICA and CCA. As a result, the interference problem in the given network topology is mitigated by the proposed algorithm, due to the optimal distribution of channels between the wireless links based on the behavior of CSMA/CA MAC protocol.

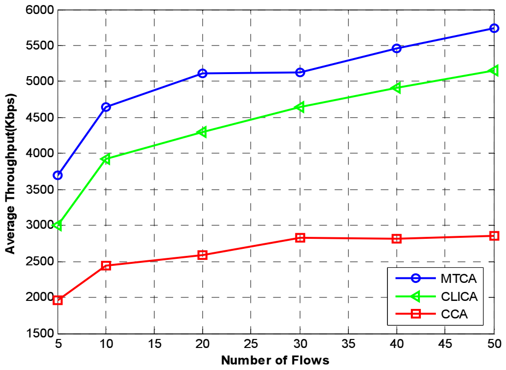

Fig 9: The average throughput of the network topology (Gateway Profile)

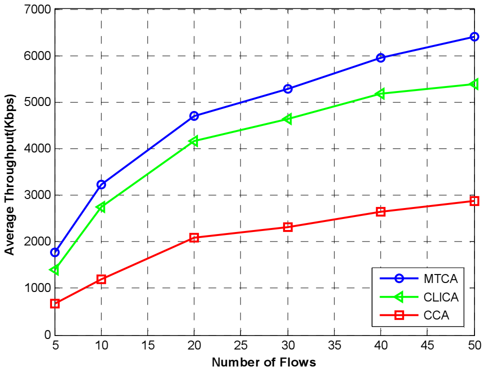

Fig 10: The average throughput of the network topology (Random Profile)

6. CONCLUSIONS

In this paper, we have proposed a new algorithm called MTCA for interference aware non-overlapping channel assignment in a multi-radio multi-channel wireless mesh network. The proposed algorithm MTCA is static and centralized channel assignment scheme. MTCA is formulated as a topology control based on removing the useless links from the original topology to mitigate the impact of interference between wireless links. Further, MTCA ensures that aggregate network throughput is fairly distributed between the interfering links by efficient utilization of the limited available channels among the wireless links while maintaining on the network connectivity. Moreover, MTCA distributes the channels between wireless links based on the radios status of the two nodes constitutes the wireless link and the behavior of CSMA/CA MAC protocol. The performance of MTCA is evaluated based on simulation model using NS-2 simulator and numerical model using MATLAB. The numerical results verify that the proposed algorithm accomplishes better performance in terms of interference, while the simulation results proved that the proposed algorithm is succeeded in avoiding the MAC collisions by efficient channel utilization and achieves better throughput than existing schemes under different network scenarios.

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