A Dynamic Channel Assignment Scheme for Multi-Radio Wireless Mesh Networks

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Abstract- ***This paper investigates the challenges involve in designing a dynamic channel assignment (DCA) scheme for wireless mesh networks, particularly for multi-radio systems.***

It motivates the need for fast switching and process coordination modules to be incorporated in DCA algorithm for multi-radio systems. The design strategy is based on a reinterpretation of an adaptive priority mechanism as an iterative algorithm that recursively allocate a set of channels to radios in a fair and efficient manner in order to minimise interference and maximise throughputs. The algorithm, called Adaptive Priority Multi-Radio Channel Assignment (APMCA) is tested for overall performance to assess the effectiveness by determining its overall computational complexity.

The combined advantages of fast switching time and process coordination modules make the APMCA a useful candidate towards automating the channel assignment method in multi-radio wireless mesh network planning and design.

***Index Terms*—Wireless Mesh Networks, Multi-radio, Channel Assignment.**

I. Introduction

One of the strategies of improving system throughputs and network capacity in Wireless Mesh Networks (WMN) is by coordinated use of multiple radios. Multiple radios wireless mesh separates client access and wireless backhaul for the forwarding of mesh traffic. In this type of mesh, each node has a dedicated radio for backhaul connectivity operating at different frequency with performance similar to switched, wired connections. One of the challenges in the deployment is that of assignment of radio channels to wireless interfaces.

Kyasanur [1] classically divided channel assignment into three categories viz: static, dynamic and hybrid. While static channel assignment is used for applications that can tolerate large interface switching delay, dynamic channel assignment (DCA) is suitable for applications with limited available bandwidth and unpredictable variable bit rate traffic. A careful review of existing channel assignment (CA) algorithms for multi-radio (M-R) systems reveals two key design challenges. Firstly, there is the need for fast switching module for switching of radio channels among the multiple wireless radios installed on each node. Secondly, there is also the need for a process coordination module for network monitoring, supervision and control. According to the author of [2], these key challenges, if properly implemented would subsequently lower the number and the cost of mesh nodes needed to deploy any community-based wireless mesh network.

In [3], a DCA a breadth-first-search channel assignment (BFS-CA) algorithm was analysed. The algorithm takes as input, the interference estimates from the mesh routers and a multi-radio conflict graph (MCG).

In the same vein, the work of H. Skalli *et al.*, as published in [4] proposed a similar algorithm called *MesTic*. The input parameter of this algorithm includes (as in [3]), a traffic matrix in addition to the MCG, connectivity graph, the number of radio at every node and the number of non-overlapping channels. Both algorithms described in [3] and [4] use ranking technique to assign channels to radios. Although this technique is simple and easy to comprehend, a rank function requires a full description of its underlying parameters and their interdependency.

In [5], a joint distributed channel assignment and routing algorithm is developed. The algorithm utilises neighbour discovery and routing protocol to allow each node to connect with its neighbour. Neighbour discovery protocol uses an ADVERTISE packet that contains the cost of reaching the gateway node. This cost in turn, depends on residual bandwidth require to achieve load balancing in the network. Conversely, the aggregate load on each virtual link also depends on a given routing algorithm. It is therefore possible to infer that the interdependency of channel algorithm on specific class of routing algorithm (also known as path selection algorithm) will not promote interoperability between devices from different vendors.

Our proposed dynamic channel algorithm will not be tied to a specific routing algorithm to ensure baseline interoperability. Also, it will not differentiate the total number of radio interfaces on each node into fixed and *switchable* interfaces. In addition, the numbers of available non-overlapped channels are expected to be far greater than the number of radio interfaces installed on each wireless node.

This paper presents a formal description and a mathematical

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model of the problem. It then proposes a multi-channel multiple radio wireless mesh network architecture. Next, the proposed algorithm is discussed with the fast switching and process coordination functional modules highlighted.. A simulation result and the analysis to compute the order of overall complexity are presented. The computation allows us to evaluate the performance of the proposed scheme and as well as simulation results. Finally a concise summary and future work conclude the paper.

II. PROBLEM DEFINITION AND DESCRIPTION

We consider the problem of assigning multiple channels to multiple radios so that each radio receives at most one channel. The wireless radios installed on each node have preferences (as stated in I) over the available channels, thus, the allocation mechanism does take the profile of the preferences as part of its inputs. An important assumption (as depicted in Fig. 1) is that the number of available channels is more than the number of wireless radio installed on each node; and that the network traffic and conditions may vary over time.

Let $G(V, E, K)$ be a connected network graph where $V = (M_p, M)$ represent a set of mesh nodes differentiated to mesh access point and mesh point respectively; and $E(u^i, v^j)$ represent a set of links. Let K be the number of wireless radios installed on each node V, and N be the number of available non-overlapped channels, denoted by $\{1, 2, , , , , N\}$

Given that the DCA considered here is closely related to random assignment problem published by Akshay-Kumar *et al.*, [6], we can formally define the problem as follows: Let the assignment of Kth wireless radio over two DCAs, p and q where K is indifferent between p and q (fairness property), be define thus

$$p \ge q \Leftrightarrow \sum_{k:k \ge ij} p_{ik} \ge \sum_{k:k \ge ij} q_{ik} \qquad (1)$$

$\forall j \in N$

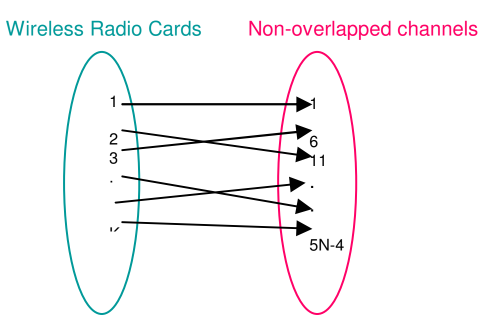

Fig. 1. Allocation of wireless radio cards to channels in a multi-radio multiple channels mesh network is modelled as Injective function (and not Bijective) function since the number of radios is less than the number of independent channels

III. ARCHITECTURE & SYSTEM DESIGN

The proposed multi-channel wireless mesh network architecture, shown in Fig.2, consists of dedicated infrastructure devices known as mesh point (MP) and mesh access point (MAP). Mesh access point is a special type of mesh point which provides access point (AP) services in addition to mesh services. Users' devices (not shown in Fig.2) support mesh services and associate with mesh APs to gain access to the mesh network. These mesh nodes are equipped with two or more wireless radio cards and together, they form ad hoc network among themselves to relay traffic to and from end-user devices. In addition, the wireless radios are running fast switching applications (this is elaborated in Section III) that allow them to support channel switching.

A dedicated centralized management information base (MIB) server is connected to the gateway. MIB server node runs the interface management protocol located within the process coordination module, and is responsible for keeping track and managing the interface switching.

As indicated in Section I, the two versions of the proposed dynamic channel assignment algorithms are implemented in the network. The version with fast switching module is implemented in the MAP and MPs, while the version with process coordination module resides in the MIB server node.

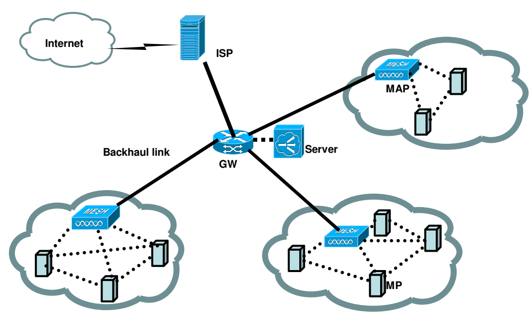

Fig. 2. A community-based multipoint-to-multipoint mesh network topology running fast switching and process coordination modules.

IV. DYNAMIC CHANNEL ASSIGNMENT

The proposed dynamic channel assignment algorithm called APMCA (Adaptive Priority Multi-radio channel assignment) is designed for a simple network structure where all the mesh nodes are equipped with equal number of radios, and a pre-defined number of available non-overlapped channels as shown in Fig.3.

The algorithm uses an iterative application of adaptive priority algorithm that terminates in (at most) N phases, where N is total number of non-overlapped channels available in the network. Adaptive priority implies that it is possible for the mesh nodes to reallocate the radio channels after each successful packet transmission from source to destination nodes subject to the channel constraints as defined in the input sequence S_i.

Each radio interface receives S_i as an input sequence which is characterised by a list of 4 elements of non-negative numbers S_i = (*NodeName*, *Non-overlappedChannels*, *NodeRadioLabel*, *AdjList*).

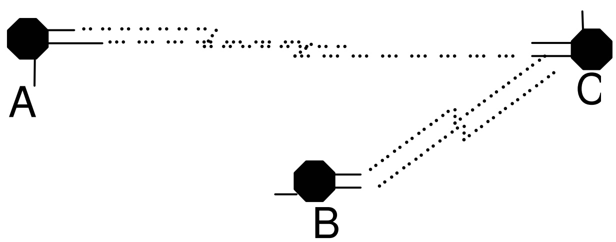

Fig. 3 Illustrates a network of three radios - four channel systems deployed in a wireless mesh network. Two of the three radios are dedicated backhaul links and the third radio is for configured for access network

At start-up, every interface is randomly assigned a radio channel such that no two radios within the same communication range (as defined by channel reuse principle) are assigned the same channel. This is done to eliminate selection biases that may degrade the network performance.

Each pair of mesh nodes to which association exist must share at least one communication channel that is used to set up a virtual link. If such common communication channel has already been established by default, then the algorithm proceeds to test the constraints as listed in *AdjList,* otherwise, a fast switching module is enabled on the source node. The mechanism of fast switching enables each wireless radio installed on the source node to randomly switch to channels available on the destination node until at least one communication channel is established. *AdjList* is a set of 2-tuples comprising the spatial channel re-use and interference estimation. The channel reuse factor depends strongly on the environmental characteristics, primarily, path loss and slow fading, while the estimation of interference depends mainly on the distance between the nodes.

A positive attempt towards the characterisation of spatial channel reuse in multi-radio WMN begins by using the concept of a simple classical triangular mesh (as given in [10]) of $L * L$ square area, and a frequency reuse distance D. Given that equal number of radios "K" is installed on each mesh node, then we have:

$$K = \frac{2L^2}{D^2\sqrt{3}} \tag{2}$$

Assuming that one MAP manages several MPs as stated in section II, and each MAP is fairly located at the centre point R, then the channel reuse ratio is calculated thus:

$$D/R \geq \zeta \tag{3}$$

where ζ is the parameter that defines the necessary and sufficient condition for good spatial reuse for the triangular mesh.

Similarly, interference estimation is based on the idea in [7] and [8] as well as a measurement based technique presented in [9]. These are adapted to a multi-radio environment. We then reduce the problem to that of estimating interference among multiple links in a wireless mesh network; and according to [5], this information is considered necessary for the design of an optimal channel assignment.

Algorithm APMCA (***A****daptive* ***P****riority* ***M****ulti-****R****adio* ***C****hannel Algorithm)* To find an efficient and fair channel assignment P of multiple radios K to multiple channels N in a wireless mesh network G(V, E, K) that maximizes capacity and minimises interference. Let H_j be a target graph, T is define as the interference threshold, and V_k denotes each radio installed on each node in the network

Step 0. [Initialise] $H_j \longleftarrow$ G (V, E, K); $P_i \equiv 0$; $P_i \in H_j$;
$|N| < K$ for all $_{i,j} \geq 1$, T = 0.65,
ζ = 1.16.

Step 1. [Iterate] testIfCommExist V =
dropWhile (V ≥ 2) [V_k|$V_k \longleftarrow$ [1..j]]

Step 2. [Channel assignment] for pair of communicating nodes
u, v ∈ V ∃ K_{ij} where Ki ∈ u
and $K_j \in$ v;
pickRadio K **rnd** = K !! **rnd**;
assignChannelToRadio K_i N_i result =
M.**insertWith** (++) N_i [K_i] result;
case intersect K_i, K_j =
filter (\C_n——>any((==)C_n)K_i)K_j **of**
{assign ——> (C_n <—— [K_i, K_j]);
nonAssign ——> fastSwitchingSame f}

Step 3.[fast Switching]
fastSwitchingSame f
lookup 'K_i ' [('K_{i-1}', Ni), ..'K_n' N_j)];
if intersect N_i N_j = [V| V<—— N_i, V 'elem' N_j]
then
swap K_i ; K_j;
else
fastSwitchingNeighbour fn

endif
lookup 'K_i' map (*D) [('K_{i-1}', Ni), ..'K_n' N_j)];
if intersect N_i N_j = [V| V <——N_i, V 'elem' N_j]
then

interferenceEsti x y z --function call;
else
reuseEsti k l r --function call;

endif

Step 4. [update process coordination server]
type State = (Integer, Bool)
update :: State ——> State
meshAccessPoint :: [a]——> (a—— >a)——>[a]
meshAccessPoint (meshPoint, K) = K+1 ++ map (*n) [meshPoint];
meshPoint :: a—— >[a]
meshPoint (radioK : radioKs) = map (t+1) [radioK];

update = [y | y <—— [meshAccessPoint(K)t + 1] !! **all**; meshPoint(n), **filter** (\y——> **any** ((==)meshPoint(K))meshPoint(t)meshPoint(t+1);

Step 5. [Interference estimation]
interferenceEsti x y z =
$$\frac{\left(\beta f^{x} yz + \Omega f^{y} xz + \Pi f^{z} yx\right)}{f_{x} + f_{y} + f_{z}};$$
-- where $\beta, \Omega, and \Pi$ are const. values that are environmental and hardware- dependent.
if interferenceEsti < T;
then
processUpdate x y z;
else
reuseEsti k l r ;
endif

Step 6. [Channel reuse estimation]
reuseEsti k l r =
let reuseDistance = $\frac{k}{0.931 * sqrtl}$;
in reuseDistance **/** r ;
if reuseEsti ≤ 1.16;
then
fastSwitchingNeigbour f;
else
$P_i = P_i + 1$;
endif

A. Complexity Analysis of APMCA

Step 0 of the algorithm APMCA requires $O(m * n)$ operations to initialise each of K number of radios installed on V number of nodes.

Step 1, the iteration step, essentially requires $O(m)$ operations to determine if there are more radios not yet randomly assigned a channel.

Step 2 is executed exactly n (m-1) times. Each execution of step 2 requires that the APMCA search through the list of assigned radios to find a pair of communicating node whose radio share a common channel. This effort requires $O(n * (m-1))$ operations, where n (m-1) denote the number of available radios m on a receiving node n.

Step 3 involves four steps divided into two categories (Same node and Neighbourhood nodes). Searching process in both the "same node and Neighbourhood node" requires β * $O(\ln(m))$ operations (where β is a constant define differently for a case of "same node" and "neighbourhood node") taking into consideration that the data in the look up tables for both cases are already sorted. Furthermore, the process of swapping of radio K_i and K_j also requires $O(1)$ operations, and on the overall, the complexity of step 3 is bounded from above as $O(\log(m))$.

Step 4 primarily involves updating of a dedicated server at every time t; and for every successful transmission from a radio K, this process requires $O(m)$ operations. For each of the notification sent to MAP, a report is sent to the server to notify the server of any changes in the state of the network. At each successive state, a 4-tuple constraint S_i, is tested and this also requires $O(m)$ operations. Since none of the other substeps of step 4 requires more than $O(m)$ operations, the complexity of step 4 is therefore bounded by $O(m)$ using the theorem:

$$O(m) + O(m) = O(m) \quad (4)$$

as depicted in [11].

Step 5 and Step 6 are functional calls, and both can be invoked at anytime during the execution process of the algorithm. Step 5 comprises two loops whose running time is proportional to the square of the number of radios on a pair of communicating nodes. In addition, a computation of the ratio $\frac{W}{U}$ requires logarithmic operations, while the test of validity of ratio $\frac{W}{U}$ has a linear running time.

In summary, the complexity of step 5 is therefore bounded as $O(m^2)$.

Similarly, *Step 6* has two linear operations for measurement of L and R. A computation of reuse distance D also requires a linear combination of quadratic and logarithmic running times. In addition, the last substep in step 6 requires a combination linear and logarithm operations. We can therefore conclude that the complexity of step 6 is also bounded by $O(m^2 * \log(m))$.

B. *Proof of Correctness*

The first step is to show that all radios are randomly assigned to at most one channel.

The next step is to conduct a randomization test only for a pair of communicating nodes.

In order that to verify the above two steps, we start by denoting the number of radios installed on a pair of communicating nodes as K_1 and K_2. If we define the number of ways of assigning the non-overlapped channels *N* as *W*, then *W* is represented thus:

$$W = \frac{N}{K_1! K_2!} \tag{5}$$

The third step is to determine how many of these ways *W* of assigning the channels to radio satisfy both the local and global constraints. This number is denoted as “assignment” P = {P_1, P_2, P_3… P_n}

The final step is to test the value of the interference estimated against the allowable threshold value.

The above four steps simply shows that a unique solution P_n exist for every pair of communicating nodes in the multi-radio wireless mesh network.

C. *Overall APMCA Complexity*

The complexity analysis shown in subsection *A* which is based on the order-of-magnitude analysis and not on the coded implementation of the algorithm shows that the overall complexity is given thus:

$$O(m*n) + O(m) + O(\log(m) + O(m) + O(m^2) + O(m^2 * \log(m)) \tag{6}$$

since K >> N, then we can conclude that $O(n) \in O(m)$ and subsequently, $O(m*n) \approx O(m)$.

Therefore, the entire complexity of algorithm APMCA computed from equation 6 is $O(m^2)$.

V. SIMULATION RESULTS

We performed a set of simulations to evaluate APMCA algorithm in different network configurations. Since the strength of this algorithm lies in the exploitation of spatial channel reuse and fast switching of the channels, the goals of these performance evaluations are aimed at determining the network throughputs and switching delay time of the radios.

For each network configuration, mesh routers are uniformly distributed in a 6 x 6 grid network with a mesh point spacing of 200 meters. The transmission range of each mesh nodes is 250m and the interference range is 550m. Every mesh node is equipped with three wireless radio interfaces, one is operating in the ad hoc mode, and the other two are operating in infrastructure mode. In addition, each mesh node support twelve orthogonal non-overlapped channels, and the bandwidth of each channel is set to 11Mbps. The packet size for all generated constant bit rate (CBR) traffic is set to 1000 bytes, and this is routed using the AODV (Ad-hoc On demand Distance Vector) protocol.

In our first set of simulations, we examine the impact of interface switching on the overall network throughputs by comparing our proposed algorithm (APMCA) with MCCA (Maxflow-based Centralized Channel Assignment) algorithm as discussed in [12]. In order to accomplish this, we create six subnet networks in our 6 x 6 grid network, and for each subnet, we randomly select the source and destination nodes and set up the traffic flow between them using TCP (Transmission Control Protocol).

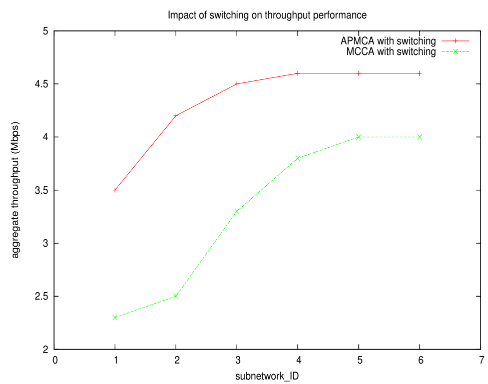

Fig. 4. Network throughput performance curves comparing APMCA and MCCA channel assignment schemes.

Fig. 4 shows the throughput performance of our proposed channel assignment scheme as compared to a similar scheme. Even though we implement fast switching function in the MCCA to establish a baseline measurement, the aggregate throughput achieve by APMCA is very significant. This is because APMCA utilizes a spatial frequency channel reuse in addition to fast interface switching function to further reduce the co-channel interferences, and consequently improve the throughput.

We also show the inferential switching error in Fig. 5 to compare the switching error in MCCA algorithm and our proposed APMCA with fast switching function enabled. We can see that for all independent measurement of the aggregate throughput for all the six subnets, the measured value is $\pm 4.5\%$ closer to the accurate estimates of the mean aggregate throughput for APMCA algorithm; and it is $\pm 6.0\%$ for the MCCA algorithm.

Our next set of simulation depicts the characteristic behaviour of our switching function in our proposed scheme. A wireless interface that requires a channel switching incurs some switching delay while making a decision on which wireless radio interface to negotiate channel switching. At the second stage, a local search for probable free channel is sought and if no channel is found, it then proceeds to the next stage for neighbourhood search.

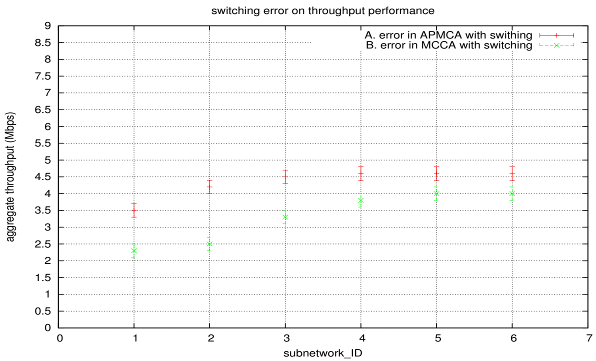

Fig. 5. Inferential switching error bars for APMCA and MCCA algorithms.

In this particular simulation, a channel is found at the neighbour node, and consequently, TCP packet is transmitted from the source to the destination node. Although, the transmission was completed at 100msec, the wireless interface was forced to retain the channel for 80msec longer using switch wait timer in order to allow the successful completion of other on-going transmissions in the network. At 180msec, the channel is released for next transmission request.

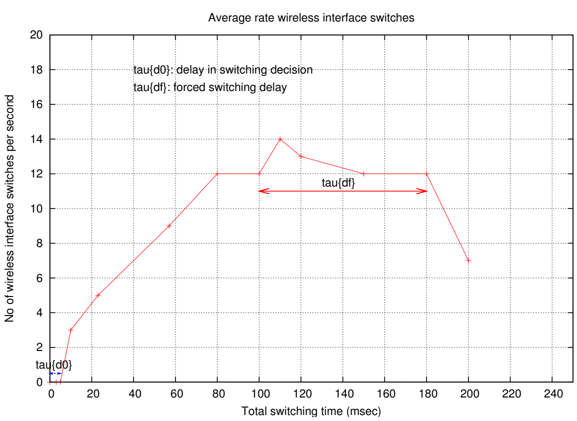

Fig. 6. Characteristic curve for wireless interface switching function for APMCA algorithm.

VI. CONCLUSION AND FUTURE WORK

This paper addresses the need for the addition of fast switching and process coordination modules to the design of channel assignment scheme for multi-radio wireless mesh networks.

Our proposed design is aimed at maximising the network capacity and minimizing the interference within the same node and among the nodes in the neighbourhood.

The study commences with architectural and system design consisting of dedicated mesh routers differentiated into mesh point (MP) and mesh access point (MAP) equipped with two or more wireless cards, and a centralised management information base (MIB) server. These infrastructural devices (mesh routers and MIB), respectively host the two different versions of our proposed algorithm. The algorithm uses an iterative application of adaptive priority scheme that terminates in (at most) N phases, where N is the total number of non-overlapped channels available in the network. The input to the algorithm is a fully connected mesh network where the number of radios installed on each node out-numbered the available non-overlapped channels. Augmented with the fast switching capability and process coordination module, the algorithm allocates channels to every pair of communicating radios in an *ordinally* efficient and fair manner. We illustrate our algorithm in detail, prove its correctness and calculate the complexity. The order-of-magnitude analysis of its overall complexity reveal a $O(m^2)$ running time, and a test of performance also demonstrate that fast switching function is a necessary module in the design of an effective channel assignment algorithm for multi-radio multiple channel wireless mesh network.

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