Channel Allocation in Multi-radio Multi-channel Wireless Mesh Networks: A Categorized Survey

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Abstract

Wireless mesh networks are a special type of broadcast networks which cover the qualifications of both ad-hoc as well as infrastructure mode networks. These networks offer connectivity to the last mile through hop to hop communication and by comparatively reducing the cost of infrastructure in terms of wire and hardware. Channel assignment has always been the focused area for such networks specifically when using non-overlapping channels and sharing radio frequency spectrum while using multiple radios. It has always been a challenge for mesh network on impartial utilization of the resources (channels), with the increase in users. The rational utilization of multiple channels and multiple radios, not only increases the overall throughput, capacity and scalability, but also creates significant complexities for channel assignment methods. For a better understanding of research challenges, this paper discusses heuristic methods, measurements and channel utilization applications and also examines various researches that yield to overcome this problem. Finally, we highlight prospective directions of research.

Keywords: Wireless Mesh Networks, Channel assignment, Multi-radio, Multi-Channel

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1. Introduction

Wireless Mesh Network (WMN) has been identified as a promising technology that covers almost all walks of life, having isolated areas like disaster recovery services, security cameras at traffic poles, connecting diverse hotspots, campus networks, battle fields, etc. [1, 2]. WMN is the architectural shift in technology from the classical wired backbone in providing last-mile connectivity [3], that has more or less the same features as of easy deployment, reliability, scalability, availability, good throughput and low cost. These networks are multi-hop, self-organized and self-healing where nodes interconnect to form a mesh. Though, only few nodes are connected to the internet via last mile gateway, but this and other similar services can be extended to the whole network. It can be envisaged as a type of converged network that combines the expertise of both wired and wireless setup qualifications i.e. ad-hoc as well as infrastructure mode networks.

Fig. 1 shows typical wireless mesh network infrastructure consisting of mesh clients, routers and gateways. Clients are the static/mobile nodes, like computers and laptops, which can also act as routers for relaying other client's data to or from the gateway. Routers act as intermediary between clients and gateway where the gateway is considered to have external or internet connectivity. The mesh routers, compared to classic routers, need lower transmission power as they have to forward packets to the nearest hops.

WMNs on one side can be simple to set up instantly while on the other hand can be more complex, having multiple gateways. Mesh networks act as a backbone and data passes from hop to hop towards the backbone. Usually, but not necessarily, WMN backbone is heavily loaded due to the traffic generated within the network and is sent outside through the gateway. Therefore, to improve the capacity and maintain connectivity, multiple channels can be utilized that are generally incorporated at the MAC layer of member nodes. Whereas mesh devices equipped with classic NICs, built on 802.11 technologies, typically allow the use of multiple channels [3]. However, to improve capacity, minimize collisions and interference, proficient channel assignment techniques are required. Exhaustive methods like assigning a single channel to each radio becomes impractical due to limited available non-overlapping channel such as three in 802.11b/g and twelve in 802.11a standard respectively [2, 3]. This leads to the problem of assigning multiple channels to different radios located nearby, simultaneously.

Backbone routers using multiple channels over single radio require frequent context switching and proper synchronization either for imposed throughput or security, which can be tricky and may result in delayed job, in order of 40-90 microseconds, and possible modification of 802.11 MAC [4, 5, 6]. Some authors [7] have implemented a TDMA style MAC protocol on 802.11 hardware and claim that average channel switching delay is 4-5 msec. Fixed channel assignment schemes are preferred in such scenarios. MIT Roofnet project, setup experiment of directional antennas consisting of 50 nodes having single interface, also faced capacity limitations and interference problems [8].

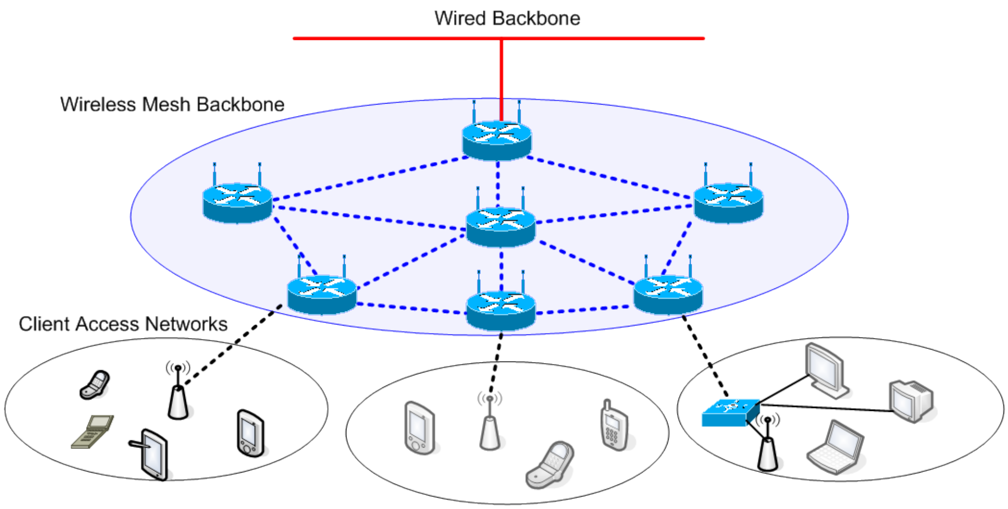

Fig. 1. Wireless Mesh Network Infrastructure

Increasing the number of radios on multi-channel mesh networks can help in reducing the number of switchings, but to achieve its true essence, proper negotiation of channel before transmission is required by the sender to know on which channel the receiver would be listening. The negotiation mechanism, however, has to follow certain restrictions e.g. any node at any specific time can be assigned at most one channel per radio [9]. For communication to take place, sender and receiver both nodes should be on the same channel. Reassigning a new channel for the communication should be for achieving high capacity, minimizing interference or both, but reassignment should properly be attempted as improper handling may affect routing, topology etc.

Characteristics of multi-radio mesh networks differ from other general multi-radio networks. In the former case, each radio has to deal with a different network, while in WMNs all radios are usually assigned to the same network [9]. In the context of the OSI layered model, physical details should also remain transparent from the upper layers, regardless of how many radios are equipped on the node. The channel assignment mechanism should not disturb routing layer services and protocols [9]. However, both channel assignment and routing are dependent on each other and may work together for increasing throughput and minimizing interference [5, 10].

In most of the proposed multi-radio multi-channel schemes, two types of assignments have been suggested. The first deals with the assignment of common channel for default radios to maintain the network connectivity, which makes it more like a single channel approach. However, such type of assignment may be of limited collision domain or full broadcast nature depending upon the algorithms in use [3, 11, 12, 13]. In the second type, remaining channels are assigned to other radios for peer to peer communication to achieve good throughput / capacity. However, this approach is mostly based on the fact that the nodes near to the wired network, e.g., gateways require more bandwidth / priority in channel assignment as they are handling more traffic. Same fact has been articulated through different approaches, e.g. rank, fat tree, cost and weight based algorithms [11, 13, 14].

Other aspects include traffic load and pattern based proposals that address the channel assignment as a cross layer problem which is dependent upon routing layer of the OSI stack as being the layer responsible for load sharing; though some have tendered it as independent [4]. Such solutions also improve Quality of Service (QoS), but due concentration should be given to avoid parallel control loops as it may have side effects of stability [15]. Another element found in the literature, maps channel assignment to the graph-coloring problem, edge-coloring complexity or conflict graph model [3, 16]. The conflict graph model can be useful in capacity estimation, channel assignment and routing related issues. This model captures link interference based on prior knowledge of hidden node's transmission and physical location of the nodes. Similarly, some proposals have divided the collision domain into sub domains through the use of groups, clusters, etc. [4, 12].

Identifying perfect channel assignment has been proven NP-hard [4]. However, strategies based on readily accessible information can be more helpful in finding satisfactory and precise solutions. This paper investigates such solutions, their limitations and highlights areas which need to be more focused upon. To the best of our knowledge, this effort is first-of-its-kind in categorizing heuristic methods, measurements and applications in the area of WMN channel assignment. Section 2 provides some useful knowledge about MAC layer; Section 3 gives an overview of media access standard of IEEE 802.11s. To provide an effective way forward in multi-radio multi-channel mesh channel assignment, section 4 reviews heuristic based channel assignment proposals by categorizing varying environments, e.g. network topology, traffic load, interference aware and channel utilization and Section 5 provides conclusion, and future research directions.

2. IEEE 802.11 Mac Layer

MAC protocols are used to ensure that packets sent to destination over the same channel do not collide with data coming from other sources. This is achieved through the use of channel access mechanisms which are part of the protocols. The channel assignment mechanism used in cellular system, e.g. FDMA, TDMA, CDMA etc. are not well suited for packet based applications, yet there are some proposals of TDMA based channel assignment for mesh networks [7, 17].

For medium sharing IEEE 802.11 uses Distributed Coordination Function (DCF) [18] which is based on CSMA/CA. Point Coordination Function (PCF) is another medium sharing mechanism implemented on top of DCF that provides support for infrastructure mode networks or networks where the nodes connect to a central entity [18]. CSMA, also called physical sensing, works on the phenomenon to sense the medium before transmitting, any node having packets to transmit, first senses the energy level of the medium and if the level is found above the defined threshold, it means other nodes are already using it and node wishing to send packets, has to wait until the channel becomes free. Collision Detection (CD) identifies collisions while transmitting, which is difficult to achieve in wireless, therefore Collision Avoidance (CA) approach is used which evades the collision before it happens by introducing backoff counter, a random amount of time that decreases with time. As the counter approaches zero node again checks medium availability, if free, it starts the transmission otherwise it again sets the backoff counter.

DCF in addition to physical sensing, optionally implements virtual sensing which determines how long it has to wait to sense the media again and this happens through the use of information travelling on the medium. This is obtained from the duration parameter in the packet's control field. Every packet is monitored by nodes listening to the medium and accordingly every such node sets its Network Allocation Vector (NAV), a timer, based on the duration value of last packet sensed. NAV uniformly decrements until reaches zero, which means now the media is idle. **Fig. 2** shows a typical NAV based media sensing mechanism. PCF and Hybrid Coordination Function (HCF), enhancements of DCF, also provide support of NAV oriented sensing mechanism.

IEEE 802.11 [19] optionally provides another virtual sensing handshake method Request to Send (RTS) / Clear to Send (CTS) for hidden node and exposed node problems in MANET. The node before transmitting packets sends RTS. The receiving node replies with CTS. All other nodes receiving RTS/CTS do not transmit during the time duration mentioned in RTS/CTS; hence collision avoidance is achieved in the proximity where communication takes place.

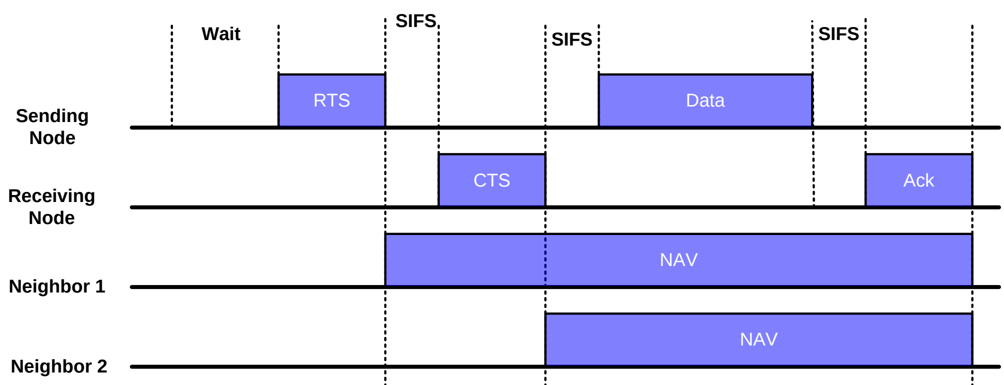

Fig. 2. NAV based Media Sensing Mechanism [5]

3. IEEE 802.11s

IEEE 802.11s [19] describes the operation of WMN. Here the mesh entity 'node' is called Mesh Station (Mesh STA), 'router' as Mesh AP and portal is known as 'gateway / bridge' that connects the mesh cloud to the external network / internet. Mesh topology is formed through active scanning using probe transmissions or passive scanning using periodic beacons. IEEE 802.11s, through the use of mesh Peering Management Protocol (PMP), properly defines the mechanism to avoid beacon collisions. **Fig. 3** shows the flow of a node from its initialization till link establishment, where neighbor discovery is accomplished through scanning with the help of a simple channel unification protocol. All Mesh STAs (nodes) use and share a profile, usually same profile to reduce the complexity, but can be different, containing three elements MESH ID, path discovery protocol / link metric identifier and path selection metric. MESH ID is same as SSID which is announced through beacons in infrastructure networks to identify access points. INITIATOR is identified by selecting a channel procedure value that is based on node's boot time. Once a matching profile is found, then the capacity is checked and on getting satisfactory response, the link is established.

Hybrid Wireless Mesh Protocol (HWMP) is used as path discovery and Airtime Link Metric (ALM) as a path selection in the mandatory profile. HWMP is an on-demand routing protocol based on Ad-hoc on-demand Distance Vector (AODV) [20]. The basic working of AODV is same however; some amendments are made in 802.11s.

From the medium access perspective, 802.11s employs Mesh Coordination Function (MCF) based on mandatory component Enhanced Distributed Channel Access (EDCA) method, which enhances 802.11e MAC DCF; using this enhancement a station may transmit multiple frames for a particular duration limit called transmission opportunity (TXOP) [21].

In order to avoid frame collisions, minimize interference and improve QoS, a distributed scheduling protocol, Mesh Coordinated Channel Access (MCCA), is used for two-hop conflict clearance. A node that wants to communicate uses MCCA opportunities (MCCAOP) that defines start time and duration. The MCCAOP *request*, containing proposed time slot that does not conflict with other MCCAOPs is sent towards the node with whom the sender wants to communicate. The other node on receiving MCCAOP *request* accepts it by replying with a MCCAOP *setup* reply. All other nodes in the communication range hear this setup reply and accordingly update their NAV and does not transmit during those times, this helps in achieving proper time synchronization [22, 23].

To negotiate other channels, Common Channel Framework (CCF) is implemented; this framework allows all the communicating nodes to periodically switch to these common channels. Networks not implementing CCF have the option to use common channel for data traffic [21, 22]. Nodes with multiple radios can use separate common channels for each radio as synchronization of these channels is done through the use of Channel Coordination Window (CCW). However, now CCF has been removed from the latest IEEE 802.11s draft [24].

IEEE 802.11s supports both single and multi-channel assignment and can be made in two ways, simple unification mode and advanced mode. But the algorithm for multi-channel is still missing, which obviously will be helpful in achieving scalable mesh networks. Similarly, to improve the network capacity, multi-radio nodes are supported in IEEE 802.11s but its implementation is left to the vendor. To overcome such shortcomings, multiple proposals on extending IEEE 802.11s MAC are found in [25, 26]. In [25] the authors have applied cognitive radio techniques over 802.11s-based WMNs by forming ISM frequency band for common control channel and non-ISM frequency band for data communication. Accordingly, two types of radios are used, i.e. ISM and non-ISM.

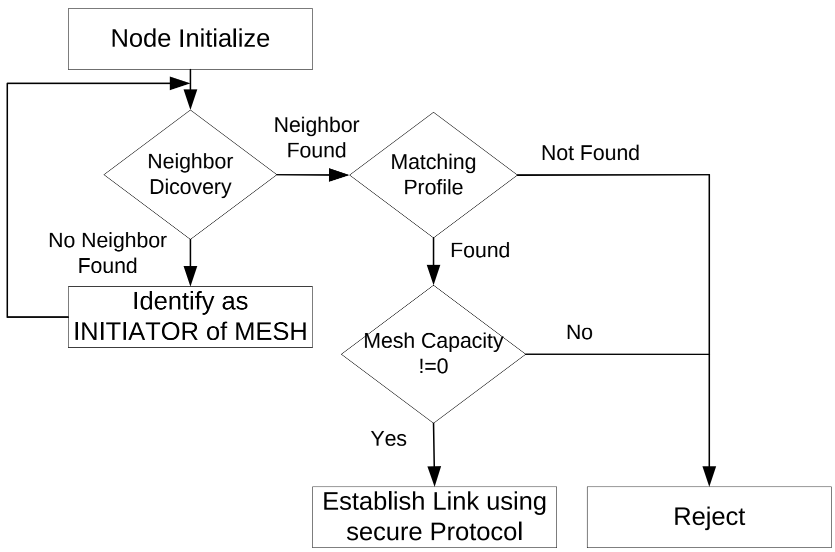

Fig. 3. Link Establishment Procedure

For data communication to take place, the information about the predefined channel, Long-Term Residency Channel (LTRC) - non-ISM band, is sent in eRTX frame. This eRTX fulfill two purposes i) Link layer connection establishment and ii) Announcement of node's absence for a particular time period and transmission duration to its one-hop neighbors. This absence period also helps destination node about planned time period regarding allocation of non-ISM band channel. Meanwhile, sending node tunes itself to the known LTRC channel. In response of eRTX the destination node replies with eCTX frame over its defined LTRC non-ISM channel rather than over the shared ISM channel. Remaining steps of sending Data and ACK remain the same.

Some other open-ended issues include implementation of frame loss probability that may be required in HWMP Airtime Link path selection Metric (ALM), as the IEEE 802.11s draft does not highlight calculation of this probability. Similarly mobility has been given very less attention, where mesh clients are usually mobility aware; hence handoff remains an unsolved problem.

4. Heuristic Based Channel Assignment Techniques

Channel assignment can broadly be classified as coordination/planning based and measurement based. Coordination based channel assignment is usually performed through some central entity, e.g. server, cellular base station controller, etc. Static, dynamic and hybrid channel assignments are examples of coordination based approach. On the other hand measure based approaches usually employ some sort of heuristics and channel assignment is planned on certain parameters like SNR, etc. This section provides an overview of such heuristics and their measurements.

4.1 Network Topology Dependent Solutions

Physical topology i.e. node surroundings, arrangements, the number of radios and physical interconnections play important role in resource allocations and becomes more critical whenever any change occur due to node failure or limited mobility. This category concerns the various proposals, which presented solutions based on network topology. In [4] authors proposed an algorithm that employs neighbor partitioning scheme, in which node partitions its neighbors into groups and each group is assigned to one of the node's interfaces. The process is repeated for every node and each group is then bounded to the least used channel within its vicinity.

A similar binding, in terms of neighbor interfaces, is performed by splitting interfaces into Up-NICs and Down-NICs to communicate parent and child nodes respectively [14]. A fat tree based routing tree is constructed and root and leaf nodes are accordingly identified. More relay bandwidth is made available on virtual links closer to the roots of trees, e.g. gateways and its nearer nodes. Each node that discovers and joins the gateway(s), further forwards the same advertisement packet to its leaf nodes instructing them to join the network through it. These advertisement packets also contain the cost of reaching wired network.

In [9] authors have proposed a graph theory based solution where mesh network is represented as undirected graph and relates it with the edge coloring problem, where channels are represented as colors. The non-overlapping channels are used so that edges with different color will not interfere with one another; however edges with similar color in the interference range are a source of collisions, these types of edges need to be minimized. The proposed static algorithm is divided into two steps: edge grouping and group coloring. Using edge grouping, vertices are obtained and line graph is colored accordingly. Vertex coloring is then transformed into the edge coloring. For broadcast traffic, every node that receives non-duplicated packets, makes copies of packets and forwards them to each of its radios. However, multi-radios cannot be directly be mapped to edge coloring.

In [27], the authors proposed an adaptive automata learning-based distributed Channel Allocation Protocol (LCAP) using probabilistic methods. Every node learns about its neighbors and their channel(s) usage by applying neighbor discovery protocol that works without the need of a common channel. To learn the neighborhood, all nodes broadcast *Hello Message* on all channels through all of its interfaces' defined channels. Access interface repeatedly switches on the remaining channels to complete the broadcast. For channel hopping, channel quit is required, which in 5GHz band is achieved through Dynamic Frequency Selection and for 2.4GHz, the authors suggested the use of NAV. The access interface plays a dual role, one as AP mode for providing connectivity to nodes and one as a monitor node to detect neighbors, etc. which is achieved through virtualization. The neighborhood information is stored in the Neighborhood Information Base (NIB) table, which consist of *NeighborTable* and *ChannelUsageList* for maintaining information of two hop neighbors and their channel usage. Opposed to others, it is handshaking / negotiation free and does not rely on assigning a particular role to any radio. Tradeoff needs to be checked between using common channel and dynamic frequency selection against the cost of switching required on access interface and their impact on power consumption.

4.2 Traffic Load / Flow Based Solutions

Traffic flow represents the stream of packets sent from source to destination [28] and it forms logical topology of any network that can contribute in finding quality channel assignment technique. Practically, predicting exact traffic demand is unrealistic. So the solution always lies in that how perfectly the traffic demands are accessed [29]. In WMNs, heavy traffic flows to mesh backbone from client nodes due to their high bandwidth demanding client applications e.g. multimedia. Following are different proposals of traffic prediction and solutions based on it.

In [4] authors have presented a centralized channel assignment algorithm that initiates with expected load, which is initially the capacity of the link, calculated by number of channels into capacity per channel divided by virtual links within the interference range. Thereafter, throughout the algorithm, expected load on a link is the sum of loads from all acceptable paths, across all possible node pairs that pass through the link. To assign the channels, algorithm then further visits virtual links in the network in decreasing order of link criticality or expected load on a link. The algorithm is repeated and each time link's capacity is estimated and the steps are repeated until the capacity / bandwidth allocated matches its expected load. The authors have presented a joint algorithm for routing and channel assignment which is iterative in nature to compose a circular dependency in the algorithm; as routing depends on the virtual links' capacity and hence is determined by the channel assignment which in turn depends on the virtual links' expected load. Such iterative nature also makes it more complicated and may require ample time to propagate [9]. A similar approach has been adopted by [30], in which channel is assigned based on calculated flow rate. In [49], the authors have worked on routing of WMN, but rather than using the traditional routing metrics, a new metric Expected Effective Capacity (EEC) is used that selects a path providing maximum throughput. To find the capacity of a link, traffic load and neighboring interference is used, whereas the share of bandwidth available to the link is based on interfering links in the interference domain.

In [13] the authors have designed a throughput oriented scheme made up of two components. The first one is the Independent Channel Characteristic Assimilation for Adaptive Routing (IC^2A^2R) protocol in multi-radio multi-channel network. The second component is a non MAC specific power control mechanism which complements the first one by favoring the channel reuse. IC^2A^2R further contains two parts; first one is the cost calculation of channel depending upon the load on the node, channel packet error rate and availability of node's interface. Second part is channel selection algorithm and the routing metric. The base line routing algorithm is AODV and selection algorithm is embedded in the route discovery step. Even if multiple channels are used, a common channel is shared by the nodes for maintaining connectivity and other control information. The route request packet is broadcasted by the source node on the common channel. Before sending a route reply packet to its neighbor, destination node firstly selects the channels (potential channels) that it shares with its neighbors. Upon receiving the route reply packet from the destination, a neighbor node chooses the least cost channel among those proposed by destination. The cost is based on load on both the sending and receiving nodes and packet error rate between the both. The same process is repeated until the route reply is sent to the source node.

To provide support for multi-channel and multi-radio in 802.11 MAC for mesh backbone, [31] presented a dynamic channel assignment protocol for media access, namely Common Control Channel (CCC) protocol, an extension of EDCA [21] used in 802.11e. CCC protocol provides two types of channels, mesh traffic channel assigned to mesh traffic radio for data messaging, and a common channel assigned to control radio for control messages and reservation of mesh traffic channels. Through the exchange of customized multichannel RTS and CTS (MRTS and MCTS) mesh channel is reserved for a particular time. All other nodes monitor and follow reserved time assigned mesh channels. Authors, mainly focused on performance evaluation of CCC protocol over network traffic, but other than control radio only one mesh radio is considered. The performance is measured using commodity MAC on the simulator and found a linear increase in aggregate throughput by a factor of seven over the EDCA. CCC protocol may perform better for smaller networks, but as the collision domain increases, there will be more collisions on the common channel.

From cognitive radio network's point of view, [32] has also highlighted the same problem as control channel saturation and has identified some other CCC design challenges e.g. security, robustness and its coverage. These challenges are then analyzed accordingly through different methods. [33] has also addressed control channel saturation and presented an analytical framework for MAC protocols based on common control channel(CCC-MAC).

The solutions for saturation provided in [32-33] are used in different perspective; however, the need is to validate these CCC challenge solutions according to mesh network environment. Performance evaluation of CCC protocol also needs to be done for multi-radios as increasing the number of radios may also increase interference and the performance achieved through traffic load heuristic in [49] may not be same.

In [33] the authors have presented a centralized channel assignment scheme that works out for network's maximum achievable throughput by means of maximum flow. The rationale behind the maximum flow approach is that schemes utilizing traffic profile for channel assignment cannot adopt dynamic network environment as traffic demands are not known in advance and also that mesh network is considered having 'multi-source, multi-sink' problem which can easily be transformed into a maximum flow problem by using super source and super sink. Their scheme works in three steps, in the first step capacity of each link is figured out, step two finds the maximum flow of all links using the maximum network flow method presented in [34] and then at the last, channels are assigned to links based on minimum interference channel to max-flow link policy. This scheme is also helpful in traffic load balance.

Similar to other researches, the authors [35] have used a hybrid approach in which static channel assignment, Common Channel (CC), is used on one of the NICs of the mesh nodes, this also helped in preserving the topology. However for data purpose, dynamic channel assignment is used on remaining NICs that works on demand basis. The demand is met using TDMA based multichannel MAC. In which each time slot is formed by two sub slots of control and data, each control slot (using CC) is consumed by the node to negotiate dynamic channels for remaining NICs. The negotiation process chooses the least interfered channel in its neighborhood. The focus of this research is on minimizing the packet delay, which is achieved through increasing the size of data slot. Authors have modified the queue mechanism and implemented multiple queues at the link layer for each of its neighbor. This, on one side decreases the waiting time in the queue and helps the node to transmit the packets of particular neighbor at a fast rate, but on the other hand increases the cost of algorithm, especially in a dense environment where many nodes would be in the 1-hop neighborhood and correspondingly so many queues will be needed on each node. Hence, tradeoff needs to be checked for both to come up with an optimized solution.

The authors [36] have discussed session based approach for channel assignment and associated a utility function with each session that shows the satisfaction level in terms of transmission. By using the Network Utility Maximization (NUM) framework from literature, all the utilities for every session are summed up to obtain a real number. Yet the channel assignment problem is mapped to be an integral problem and thus a heuristic algorithm for transforming the summed up value to an integer value is recommended. The algorithm works by assigning all available channels to all the links and then removes the conflicting channel in terms of neighborhood until it satisfies a particular threshold. This algorithm works in a distributed fashion until all nodes fulfills the defined criteria.

Most traffic based algorithms [4, 13,], [30-32] are based on anticipated traffic load/pattern which takes considerable time to reach to a stable state, i.e. until the actual traffic flows and the algorithm are re-calculated based on factual values. Similarly in the group based algorithms, the management of groups becomes difficult due to the distributed nature of WMNs.

Cross-layer schemes have always remained performance oriented solutions, whether it belongs to mesh routing or the medium access [4, 10, 30, 37]. Routing influences interference and load, whereas channel assignment influences topology and capacity. IEEE 802.11s is based on HWMP [23], which through its routing table shares a lot of routing information about its neighbors, which can easily be extended with channel allocation information for multi-radio mesh networks.

4.3 Interference Aware Solutions

The capacity of a link depends on bandwidth and signal to noise and interference ratio, as Shannon's Theorem states $C = B \log_2 (1+S/N)$. In addition to bandwidth limitations in wireless, three channels in 802.11b/g and twelve in 802.11a standard respectively [2, 9], wireless media are more prone to noise and interference and in WMNs interference has always an effect on channel assignment when implementing single/ multi-channel solutions. But the magnitude of interference aware channel assignment technique increases when multi-radio networks are deployed. Though interference can be minimized, but cannot be completely removed due to the limited number of non-overlapping channels available. In this view, different methods proposed in the literature giving weight to interference are discussed as follows.

The hypothesis of [12] was that non-coordinated interference has severe impact on channel utilization and it was based on comparison of coordinated and non-coordinated interference under the CSMA/CA protocol. The Cluster-Based Channel Assignment Scheme (CCAS) uses frequency reuse concept of cellular networks while logically partitioning the nodes into non-overlapping circular clusters where each cluster circle depends on the carrier sensing range of nodes. To control the inner working of the cluster, assumption of presence of Cluster Head (CH) is made. Each node in the cluster joins CH through active or passive scanning.

To minimize the non-coordinated interference, CH identifies other CHs whose nodes are creating non-coordinated link to the node of first CH. A list of such CHs is maintained at each CH and shared with the CCAS server which resides with any gateway. Based on these statistics servers assign default channels to every CH by keeping in view the carrier sensing range. For intra-cluster communication default interface / channel is used and for inter-cluster non-default interfaces are used. Each inter-cluster link is visited sequentially and assigned the default channel of transmitter node. Verification step is also performed to search for alternative channels if the non-coordinated interference is found.

In [38] the authors have presented Routing over Multi-radio Access Network (ROMA), a protocol that works to achieve better throughput by choosing an optimized routing path and channel based on quality links towards the gateway. ROMA is a distributed joint protocol, unlike the centralized joint protocol approach as used in [4, 39]. But contrary to existing approaches like [4, 25, 39], ROMA has not used common channel. When a node have data to transmit, it first finds out the best gateway path by using path metric, and then follows gateway channel sequence to assign channels to the path. To build the link metric, the author has used famous delivery ratio metric ETT (Estimated Transmission Time) which estimates the packet transmission time based on ETX (Estimated Transmission Count) metric, packet size and link capacity [40]. However to estimate link quality author used two additional factors, link variation/ fluctuations and external load. To select a channel, the level of each node is calculated by the number of hops it is away from the gateway and assigns channels according to gateway’s sequence; here seed is the gateway sequence which initially is c1, c2, c3, etc. Assuming every node has 2 radios, a 3 hops away node will be assigned c3 and c4 channels and similarly 4 hops away will be assigned c4 and c5 channels on their respective radios. This scheme works fine for single radio single gateway and also for two-radio single gateway. It can also be extended easily for more radios, however for multiple gateways interference minimization mechanism is provided, which initially scans the non-overlapping channels and monitors them for a particular time to know about other gateway's channel usage. After that it choose the seed, a gateway sequence, such that the channels, on one hop distance of gateway, do not interfere with other gateways' channels.

Theoretically, channel assignment approaches based on minimized interference may be helpful for some specific WMN solutions such as the conflict graph approach for non-interfering links [41-42]. But, practical deployment of WMNs may have to face the noise / external interference as well that can severely affect performance.

4.4 Auxiliary Approaches:

Channel assignment suffers from many factors and hence propositions based on only one may not provide a satisfactory solution. Following are different proposals based on more than one factor.

Traffic Load Aware and Network Topology Dependent: The efficiency of traffic aware solutions depends on the physical topology also, as highlighted by [29]. In [11] the authors have proposed hyacinth architecture influenced static centralized channel assignment scheme that is based on ranking, whereas rank determines the priority of channel assignment which is calculated from its traffic and topological characteristics (aggregate traffic at node based on offered load, distance of the node from gateway, radio interfaces on node). While gateway, being the node having more traffic, is assigned the highest priority. The algorithm assigns channels based on the highest rank and picks the neighbor with whom the node has communicated most but assigns the least used channel. The process is repeated until all nodes/ interfaces have been assigned the channels. Connectivity is ensured by using a common default channel. Initial Load used is same as calculated by [4].

Interference and Network Topology Dependent: In [39] the authors have provided a joint solution, as channel assignment effects link bandwidth and are dependent on the routing. The mathematically formulated interference free link scheduling model is presented based on interference, number of channels and number of radios. The authors have suggested a scheme for fair allocation of bandwidth using existing commodity hardware. However topology setup has not been discussed and the authors have assumed that traffic is dynamic but has statistical patterns.

The mesh backbone is mapped in terms of a directed graph which leads to a flow graph. The algorithm takes interference into consideration and transforms traffic. For simplification, it is divided into three steps, channel assignment, flow transformation and link flow scheduling. Initially by partitioning the flow assignments, rough assignment of channels is made to get the flow on the flow graph, then the flow is adjusted and finally based on the adjusted flow and duplicated assigned channels, more optimum channel assignment is made.

Another auxiliary approach found in [43-45] is more focused on physical topology, due to the dynamic nature of traffic and non-prior knowledge of traffic flow. Based on local available information (interference cost), the algorithm allows each node to choose a less interfering channel without considering the receiver's listening state. The algorithm is recursive in nature to improve its selection until it stabilizes (lower interference level). In this proposal stabilization depends on the assumption that, at a time, only one node can switch its channel. This type of assumption is difficult to achieve in dynamic environment due to non-availability of proper synchronization mechanism. However, for this purpose every node shares its channel information with its interfering nodes, so when a node changes its channel it should be fully aware of channel information of at-least its surrounding nodes. The focus of the algorithm remains on placing the replica (channel) on a far location in the network. As in other proposals, this scheme also assigns one radio to common channel for control and connectivity purpose.

Table 1 provides an overview of the proposed techniques being used in channel assignment strategies in the near past. Broadly, these techniques can be classified either in centralized or distributed approaches. WMN majorly consists of a wired entity (or more), which as discussed earlier acts as a central authority, so much so that even provides keys to mesh routers for encrypted communication. This seems to be the main reason that the majority of the proposed techniques has focused on centralized approach. However, in case of dense environment or distant clients, the responsibility is being shifted on the mesh routers and hence distributed approach is used. This way, even though a fairness approach is proposed via using multiple channels, but the main issue arises in terms of synchronization of mesh clients which are having only single antenna but are in the range of multiple MRs.

Table 1. Summary of some near past Channel Assignment Algorithms and Protocols

Algorithm/ Author	**Heuristics**			**CA Scheme**			**Approach**	
	Inference	Traffic	Topology	Static	Hybrid	Dynamic	Centralized	Distributed
MCCA [2]			√			√	√	
BFS-CA [3]	√					√	√	
MESTIC [11]	√	√		√			√	
Raniwala [4]		√				√	√	
MPLGG [16]	√			√			√	
LCAP [27]	√		√			√		√
DeSARA [30]		√				√	√	
ADCA [35]	√				√		√	
HCAA [36]		√				√		√
ROMA [38]		√				√		√
Anand [41]	√			√			√	√
ITACA [46]	√	√			√		√	
MC-CC-CA [47]		√		√			√	
Hyacinth [48]		√				√		√

Moreover, the load at MRs near gateway(s) makes it hard to have a linear solution that is typically applied at the leaf levels or disperse scenarios. Hence, consideration of multiple factors independently makes distributed approach hard to implement. However, statistical/ dynamic models and algorithms can still be applied on the basis of traffic patterns or SNR, which can vary at each level of the network topology; as linear solutions may fail for heavy or real time applications. Additionally, the broader classification can be divided in terms of channel assignment schemes that can be static, dynamic or hybrid in nature. Static is the simplest in nature where channels once allocated are fixed and fairness is provided in terms of other quality parameters, which have their rigid thresholds. To overcome this approach, dynamic channel assignment based on traffic load and throughput was introduced and emphasized. However, for a large number of clients having varying flows, dynamism introduces more complexity and the overhead involved is quite large in terms of the gain. Hence, as suggested in interference and traffic aware channel assignment (ITACA) [46], hybrid scheme is found more flexible where all channels assigned to MRs are not changed but the only on-demand basis. Nevertheless, the focus being in the above discussed proposed techniques is about fairness, therefore parameters such as traffic and interference are mainly considered for WMN deployments. However, MCCA [2] has highlighted to cater for topology in terms of provisioning of fairness to clients and acquire good throughput.

5. Conclusion and Future Directions

We have discussed channel assignment measurement based approaches for wireless mesh networks proposed in the recent past and tried to present complete theoretical and practical description of channel assignment schemes, their requirements and application scenarios. Many excellent approaches have been discussed that account for different factors and accordingly, adopted solutions are highlighted.

To find a proper rationale we have classified the heuristics based on their methods and measurement techniques as Network Topology dependent, Traffic Load / Flow based, Interference aware solutions and some auxiliary approaches that are combination of above. Most of the approaches found are using Interference and Traffic aware heuristics and less attention has been given to Topology control. Topology has a key effect on performance of mesh networks with respect to channel assignment and hence, cannot be totally ignored.

For an ideal and optimum solution closer to real life problem of channel assignment, rather than just taking care of only one approach and optimizing it, an all-rounded approach is needed which intelligently offers proper weighting of all factors influencing channel assignment and can also satisfy future requirements. Additionally, heuristic methods aid in decision making by judging current behaviour and come up with optimization techniques.

Though, the paradigm has shifted from static to dynamic and ultimately towards hybrid CA schemes, as discussed earlier. But a central entity is needed to collect and analyze various dynamic parameters and decide according to a threshold level. Thus, hybrid schemes are generally considered suitable for centralized approach. Nevertheless, the hybrid design can be altered for distributed approach in a way where initially each node is autonomous for the decision making of its own traffic handling, but ultimately collateral / consensus based techniques need to be incorporated to underline a static threshold for cumulative decision making; which can be changed on the fly by the concerned nodes.

Despite the fact that WMN acts as an adhoc network, the gateway being the central entity is more focused in terms of topological constraints. Therefore, most approaches are centralized in nature, but distributed approach having dynamic or hybrid scheme is still an open-ended research domain. Furthermore, the communication overhead can be minimized by applying agent-based approaches; either Multi-agent system that covers the whole WMN or agent-based modelling such that communication cost can be minimized; especially as multi-radio multi-channel environment reflects quite many communication on the control plane.

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