Channel Assignment Techniques for Multi-radio Wireless Mesh Networks: A Survey

A. B. M. Alim Al Islam\textsuperscript{1,2}, Md. Jahidul Islam\textsuperscript{3,4,5}, Novia Nurain\textsuperscript{6,7}, and Vijay Raghunathan\textsuperscript{8}
\textsuperscript{1,8}School of ECE, Purdue University, West Lafayette, IN 47907-2035, USA
\textsuperscript{3,6}Department of CSE, University of Minnesota, Twin Cities, Minneapolis, MN-55455, USA
\textsuperscript{2,4,6}Department of CSE, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh
\textsuperscript{5,7}Department of CSE, United International University, Dhaka-1209, Bangladesh
Email: \{\textsuperscript{1}abmalima, \textsuperscript{8}vr\}@purdue.edu, \textsuperscript{2}alim_razi@cse.buet.ac.bd, \textsuperscript{3}islam034@umn.edu, \{\textsuperscript{5}jahid, \textsuperscript{7}novia\}@cse.uiu.ac.bd

Abstract—With the advent of multiple radio interfaces on a single device, wireless mesh networks start to achieve significant improvement in network capacity, latency, and fault tolerance. The improvement is achieved through concurrent transmissions over different channels utilizing the multiple radio interfaces. However, the introduction of different channels over multiple radios on single mesh node compels to retrospect different issues such as interference, channel diversity, and channel switching from novel perspectives. Due to these novel perspectives, conventional channel assignment techniques proposed for single-radio wireless mesh networks are not generally applicable to the multi-radio cases. Consequently, we have to reconsider the different issues while making a trade-off among all the available channel assignment options to extract the best performance from a multi-radio wireless mesh network. There are a number of research studies that propose various channel assignment techniques to extract the best performance. In this paper, we present a comprehensive survey on these studies. First, we point out various design issues pertinent to the techniques presented in the studies, and adopt the issues as the basis of our further discussion. Second, we briefly describe several important already-proposed channel assignment techniques. Third, we present a number of channel assignment metrics that are exploited by the already-proposed techniques. Then, depending on the considerations in these techniques, we categorize the techniques and present an exhaustive comparison among them. Nevertheless, we point out a number of real deployments and applications of these techniques in real scenarios. Finally, we identify several open issues for future research with their current status in the literature.

Index Terms—Wireless mesh networks; channel assignment; multi-radio systems.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) have emerged as a new key technology in the evolution of wireless networks over the last decade or so. The reasons behind such emergence are some distinguished properties of WMNs such as self-organization, spatial reuse, and fault tolerance. A WMN achieves these properties using dual-functioning nodes that automatically establish and maintain connectivity among themselves. The dual-functioning property of a mesh node covers the operation as a client and the operation as a router in forwarding packets on behalf of other nodes that may be outside of the carrier sensing range of corresponding destinations. Such ad-hoc connectivity due to the dual functionality enables WMNs to achieve a number of advantages such as low cost, ease of maintenance, reliability, and robustness. These advantages of a WMN make it suitable for numerous applications [83], [84], [85], [86], [87] such as broadband home networking, transportation systems, building automation, health and medical systems, backup networks, etc.

At the early age, mesh nodes in a WMN followed conventional wireless network standards through being equipped with only one radio per node that operates over a shared channel. In this design, end-to-end data flow experiences substantial interference from ongoing transmission of both nearby simultaneous flows and nearby hops of the same flow. Therefore, a new architecture exploiting multiple radios on each node, having multiple available channels, has come to light. This architecture is commonly termed as multi-radio WMNs. It alleviates the interference problem, which exists in the single-radio architecture, to a great extent through the introduction of multiple channels over the radios available on a single mesh node [81]. Moreover, it extends its usability by enabling simultaneous transmission and reception exploiting the multiple radios from a single mesh node. Nevertheless, another performance boost is obtained by achieving enhanced reliability and robustness through the exploitation. Therefore, the multi-radio architecture becomes a popular networking paradigm in recent times.

The advantages of multi-radio WMNs encourage commercial deployments in pragmatic applications. Moreover, significant reductions in the price of a network interface card and the availability of multiple channels in both IEEE 802.11 and 802.16 frequency band promote a number of recent WMN proposals and deployments that utilize multiple radios with multiple channels. However, we cannot achieve the full strength of multi-radio WMNs unless we efficiently perform a number of important tasks such as channel assignment, routing, and link scheduling [55]. Among these factors, channel assignment has become the most prominent one to be investigated in the recent research studies as it provides a basis of improvement to the other ones owing to the significant interrelationships between it and the other two tasks.

Now, different channel assignment techniques [119], [120] have already been proposed for single-radio WMNs. How-
ever, different aspects related to data transmission over wire-
less channels such as interference, channel diversity, channel
switching, etc., significantly vary over single-radio and multi-
radio WMNs. Therefore, the channel assignment techniques, 
which were originally proposed for single-radio WMNs, can-
not be directly adopted in the multi-radio cases. Consequently, 
a number of different channel assignment techniques for multi-
radio WMNs have been proposed in the literature. Several 
research studies [34], [90], [99], [104], [115], [117], [118] 
attempt to investigate these already-proposed techniques from 
different perspectives. For example, the studies in [34], [117] 
present only concise categorizations of the techniques dis-
regarding different important aspects such as design issues 
pertinent to these techniques and metrics used in channel 
assignment. Besides, the study in [115] specifically accounts 
for only a subset of the techniques available in the literature. 
Therefore, we need a more comprehensive and complete 
analysis over the state-of-the-art techniques to efficiently ex-
tract their underlying essences and to consider them from 
different application perspectives. Having this goal in mind, 
in this paper, we conduct a thorough study over the channel 
assignment techniques for multi-radio WMNs that are already 
proposed in the literature. Based on our study, we make the 
following set of contributions:

- We identify all the design issues that are pertinent to the 
task of assigning channels over multi-radio WMNs.
- Subsequently, we briefly describe some important chan-
el assignment techniques grouped by their underlying 
methods.
- Next, we illustrate the metrics that have been utilized in 
the already-proposed channel assignment techniques.
- Then, we present an exhaustive categorization of the 
already-proposed channel assignment techniques based 
on five different aspects: point of decision, dynamicity, 
granularity, underlying method, and spanning layers in 
OSI. Besides, we compare these techniques from the per-
spective of all design issues based on the considerations 
made by the techniques.
- Finally, we discuss some real deployments of WMNs 
and the applicabilities of the different channel assignment 
techniques in pragmatic scenarios.

We organize the rest of this paper as follows: We identify all 
the fundamental design issues related to channel assignment 
in multi-radio WMNs in Section II. Most of the state-of-the-
art channel assignment techniques address one or some of 
the design issues. We provide concise elaboration of some 
important state-of-the-art techniques along with their strengths 
and limitations in Section III. These techniques use different 
metrics while addressing the issues. Therefore, we briefly 
describe all the different metrics in Section IV. Next, we 
present a taxonomy for the state-of-art channel assignment 
techniques in Section V. We present an exhaustive compar-
ison among these techniques in Section VI. Then, we illustrate 
different real deployments along with the applicability of these 
techniques in Section VII. Finally, we envision some future 
work for channel assignment in multi-radio WMNs in Section 
VIII and we conclude this paper in Section IX.

II. DESIGN ISSUES

Channel assignment techniques for multi-radio WMNs at-
tempt to optimize network performance from different per-
spectives. Consequently, the issues considered by different 
techniques in the literature exhibit significant variation. We 
identify all of these issues to use them as the basis of our 
further discussion. Therefore, first, we briefly describe the 
issues to provide necessary background used later in this paper.

A. Connectivity

If a channel assignment algorithm can maintain at least one 
possible connection between each pair of nodes in a WMN, 
then the algorithm is considered to achieve connectivity. For 
example, in Fig. 1, all nodes are equipped with two interfaces 
with four available channels. In Fig. 1a, channel assignment 
forms one connected component in the network as all nodes 
can communicate with each other with the available interfaces. 
However, if we change the assigned channel between A-
B from channel4 to channel1 (as presented in Fig. 1b), then B 
and D do not have any additional interface left to 
assign a common channel to retain an active link in between 
them. Therefore, this assignment divides the network into two 
connected components (A, B, C) and (D, E, F), and thus 
loses connectivity of the original network topology.

Connectivity is very important for channel assignment al-
gorithms, which mainly attempts to maximize the number 
of allowable transmissions. Additionally, while considering 
maximization of the number of allowable transmissions, we 
need to consider another important issue called interference.

B. Interference

If two nodes try to simultaneously transmit data on the 
same channel and both of their transmissions can be sensed 
from a common position, then they garble the data of each 
other at that position and cause interference. Interference in 
wireless networks is generally classified into three different 
types [33] - intra-flow, inter-flow, and external. If different 
simultaneous transmissions of the same data flow interfere 
with each other, we call it intra-flow interference. On the other 
hand, if simultaneous transmissions of different data flows 
interfere with each other, then we call it inter-flow interference. 
Finally, if transmissions from any device outside of a WMN
interfere with transmissions from any node inside the WMN, then we call it external interference.

The simplest approach to capture interference is Primary Interference Constraint [2], [15]. This constraint indicates interference between two links if and only if those links share at least one end point. Other two models [35] in the literature, called Protocol Model and Physical Model, discover interference in more realistic manners. Protocol Model assumes two different ranges for transmission and interference. It generally considers a longer interference range than transmission range. This model imposes two constraints for successful data transmission - 1) The immediate destination node must be within the transmission range of the source node, and 2) The immediate destination node must not be within the interference range of any node other than the source node. On the other hand, Physical Model imposes a constraint for successful data transmission that the Signal to Interference and Noise Ratio (SINR) at the receiver must be larger than a threshold value. Between the two models, the Physical Model is more realistic than the Protocol Model, whereas the Protocol Model is simpler than the Physical Model. Channel assignment using a realistic Physical Model requires more frequency channels for network throughputs at different node-degree constraints as compared to using simpler Protocol Models [110].

In addition to the interference model, we have to consider three other constraints [17], which control the level of interference. The first constraint limits the number of available channels, as we cannot avail as many non-interfering channels as we require due to technical facts and government regulations. The second constraint limits the number of available radio interfaces, which in turn limits the usage of all available non-interfering channels. The third constraint is on node placement that determines vicinity of the nodes, which in turn determines the extent of interference for a certain number of available radio interfaces and channels. For example, in the Protocol Model, node placement mainly controls the interference range, which is considered to be 2 ~ 3 times of the transmission range.

In summary, we have to consider three different types of interferences using an interference model for efficient data transmissions. We also have to take into account the constraints on the number of available channels, number of radio interfaces, and node placement to alleviate interference. One common technique that can alleviate the interference to some extent is channel diversity.

C. Channel Diversity

The extent to which all links within the interference range of a mesh node are assigned to non-interfering channels is expressed as channel diversity. Fig. 2 depicts the impact of channel diversity. In Fig. 2a, all the links are assigned to channel 1. Therefore, none of the nodes can perform two simultaneous transmissions. In Fig. 2b, channel diversity is imposed by assigning two links to channel 2. Therefore, two nodes (A and C) are able to perform two simultaneous transmissions. However, retaining the same channel diversity in Fig. 2c, all nodes are able to perform two simultaneous transmissions independently. Obviously, the third channel assignment is better than the second one. To measure the efficiency of such channel diversity, we have to consider a new metric called throughput.

D. Throughput

Throughput (also denoted as cross-section goodput [28], [31]) of a WMN is defined as the average rate of successfully transmitted bits over the network. Channel assignment controls effective utilization of bandwidth, and thus regulates the throughput. Such effective utilization of bandwidth ensures a lower number of retransmissions, which in turn indicates lower end-to-end delay for successful transmissions. The end-to-end delay not only depends on the number of retransmissions but also on queuing delay [25], [29], channel switching delay [88], and transmission delay [89].

Most of the research studies attempt to maximize network throughput by minimizing the transmission delay. However, in the case of non-uniform traffic, in a WMN, only such minimization consideration of the transmission delay will not be enough for improving network performance. We have to consider another metric - load balancing, which we discuss next.

E. Load Balancing

Different links of a network may have different data transmission rates. Available radios to be assigned to these links also may operate over different channels with different bandwidths. Consequently, the radios may exhibit different data rates. In such cases, assigning channels to these links, retaining a balance between data transmission rates of the links and data rates of the radios, is termed as load balancing. For example, in Fig. 3, let, the radio operating over channel 2 has a higher data rate than the radio operating over channel 1. Besides, A - B and C - D have higher data transmission rates than that of A - D and B - C. Now, both channel assignments in Fig. 3a and Fig. 3b have similar overall transmission delays over the channels as they both assign the same channels in alternate links to minimize interference. However, the channel assignment in Fig. 3b maintains more balance between the data transmission rate of links and data rates of the radios than that in Fig. 3a. Therefore, the channel assignment in Fig. 3b is more load-balanced that that in Fig. 3a.

Load balancing is mainly required to adapt dynamically changeable behavior of network traffic. In some networks, not only traffic but also network topology may change dynamically. Therefore, channel assignment should consider another metric - dynamicity.
Good load balancing

Fig. 3: Impact of channel assignment on load balancing

F. Dynamicity

The property to adapt dynamically changeable behavior of a network is termed as dynamicity. It is an essential property for the channel assignment algorithms that are intended to be operated in a WMN with frequently changing topology, traffic, environment, etc. An efficient algorithm should be updated with the current status of the network during its operation. However, there must be some overhead for the control messages that contain information about the current status of the network. Therefore, we have to consider another metric - control overhead.

G. Control Overhead

The operating cost associated with the network control message (such as the HELLO packet to indicate the presence of a node) is termed as the control overhead. There are a number of modes of transmissions for the control messages, e.g., unicasting, multicasting, broadcasting, and three way handshaking. Among them, three way handshaking incurs the highest overhead and unicasting incurs the lowest overhead. Whatever mode we follow, total control overhead also depends on the data length and quantity of the transmitted control message. For example, control messages about only the locally reachable nodes require less overhead than those about all nodes in a WMN because of the shorter data length of control messages. This phenomena raises the requirement of consideration of another metric - locality of information.

H. Locality of Information

Information about only the neighbor nodes has more local essence than information about all the nodes in a network. Transmission of a packet containing the local information requires less overhead than that of a packet containing global information. Therefore, an increase in the locality of control information implies less control overhead. Here, the locality of information does not indicate the locality of decisions in channel assignment. Locality of decision mainly depends on the points of network that take the decisions. This is related to distributive nature of an algorithm.

I. Distributiveness

Some channel assignment algorithms [18], [28], [30] take global decisions from a central point whereas some algorithms [3], [9], [29] take local decisions from all nodes in a WMN. The extent to which an algorithm can enable the mesh nodes to take own decisions indicates the distributive nature of the algorithm. If the individual decisions change frequently, then a WMN may face high overhead to propagate them. Moreover, the frequent changes in decisions threaten stable operation in a WMN. Therefore, distributed channel assignment algorithms should guarantee an important property - stability.

J. Stability

There are two types of phenomena that result in violation of the stability - oscillation and ripple effect. Fig. 4 depicts both of these phenomena.

Oscillation can occur due to frequent changes in channel assignment decisions. For example, in Fig. 4a, there are two available channels. Node A assigns channel1 and channel2 to links A − B and A − D respectively. Now, A wants to assign the less utilized channel to the link A − C. At first, A randomly chooses one of the channels. Let the randomly chosen channel be channel1. However, as soon as it chooses channel1, utilization of channel1 gets higher than that of channel2 and thus it has to change the assignment to channel2. Again, it has to change its decision as this time utilization of channel2 gets higher than that of channel1. This process continues and results in a ping-pong effect. We can overcome this sort of oscillation using the notion of a threshold, which must be crossed before changing any decision that is already taken.

Ripple effect mainly occurs when a change in decision requires a number of propagations through the network. For example, in Fig. 4b, all nodes A, B, and C use only one interface to maintain connectivity among them using channel1, and none of them has an interface tuned to channel2. If at any point of operation A decides to switch its interface from channel1 to channel2, then, to continue data transmission on link A − B, B also has to switch its interface to channel2. Similarly, to continue data transmission on link B − C, C also has to switch its interface to channel2. Therefore, changing the decision in only one node imposes incremental changes on the other two nodes.

Both oscillation and ripple effect reduce data transmission efficiency due to traffic interruption and considerable amount of delay involved in channel switching. Therefore, we should
take necessary steps to ensure stability to increase the applicability of an algorithm. However, ensuring stability gets more challenging in WMNs having mobile nodes. Therefore, channel assignment algorithms should consider another important property - client mobility.

K. Client Mobility

Mobile clients can access WMNs by dynamically connecting to the mesh nodes. As a mobile client moves away from a mesh node and gets closer to another one, it should switch its connectivity to the newly closest node. This connectivity change involves a transition (hand-off [37]) from one mesh node to another mesh node before being able to continually communicate with the WMN. A channel assignment algorithm has to adapt the change in position of the client as it is required to establish a new route with a new channel to continue connectivity. Such adaptation also partially deals with the unexpected phenomena of experiencing faulty connection in a network. Consequently, we need to specifically consider another metric called fault tolerance.

L. Fault Tolerance

There are different types of faults that may force a WMN to suffer from a degradation of its performance. These faults can be broadly divided into four categories [38] - transmission link fault, network element fault, mesh protocol fault, and traffic congestion. Channel assignment algorithms should quickly adapt to transmission link fault and traffic congestion. One of the methods used by some channel assignment algorithms to adapt these faults is to store information about alternate channels that are able to maintain connectivity [31].

M. Other Design Issues

So far, we have identified some key issues that must be considered by most of the channel assignment algorithms intended for multi-radio WMNs to maintain its minimal efficiency. In addition to these, there are some other issues that should be considered to ensure high efficiency and applicability of a channel assignment algorithm. These issues are convergence rate, scalability, synchronization, fairness, use of a fixed common channel, etc.

Convergence rate of an algorithm refers to the time required by the algorithm to converge to a final decision. High convergence rate of a channel assignment algorithm indicates a small time requirement for finding the ultimate channel assignment decision, which is essential for the applicability of the algorithm. However, even a high convergence rate may not be enough to ensure efficient operation of a channel assignment algorithm in large scale WMNs, if it is not scalable. Different phenomena can undermine the scalability of an algorithm. For example, if an algorithm requires broadcasted information to make its decisions, then the algorithm may lose its applicability with the increase in size of a WMN due to the requirement of more transmission power involved in the broadcasting. Besides, if an algorithm has a time complexity that is somehow proportional to the size of a WMN, then the algorithm may become slower in a large-scale network.

Nonetheless, fairness is another important issue to consider for designing channel assignment algorithms in WMNs. It implies maintenance of balance among usages of different available channels by the mesh nodes. To achieve a high degree of fairness, channel assignment algorithms must ensure synchronization of selection of channels for WMN links. We can achieve synchronization using scheduling algorithms [55]. Usage of a fixed common channel is another way of ensuring synchronization [4], [6], [10].

Considering the design issues presented above, a number of channel assignment techniques have been proposed in the literature. These techniques exploit several metrics for assigning channels. Next, we briefly discuss some prominent channel assignment techniques and the metrics used by them.

III. DIFFERENT CHANNEL ASSIGNMENT TECHNIQUES

We group some important channel assignment techniques based on their underlying methods\(^1\) and briefly describe them in the following subsections. In our description, we present graph-based, mathematical formulation-based, AI-based, peer-oriented, and greedy techniques in sequence. We start with the graph-based techniques.

A. Connected Low Interference Channel Assignment (CLICA)

CLICA [17] is a DFS-based channel assignment algorithm that uses a greedy heuristic to find a connected low interference topology in a multi-channel WMN. It starts by constructing a weighted conflict graph from the connectivity graph following the Protocol Interference Model. This graph contains node priorities and edge weights, which reflect the extent of interference between two links in the connectivity graph. CLICA assigns channels to the links based on the priorities following a greedy heuristic with the similar essence of graph coloring. The greedy heuristic minimizes either of two metrics - maximum link conflict weight or average link conflict weight over all interfering links. It uses an adaptive priority algorithm, which alters a node’s priority during the course of execution to ensure connectivity. Finally, it pairs unassigned radios either in the same greedy manner or based on the traffic load. Another technique, INterference Survival Topology Control (INSTC) [27] minimizes maximum link co-channel interference with a simplified objective function that resembles the minimization of the maximum link conflict weight in CLICA.

CLICA decreases interference while maintaining connectivity by a simple polynomial time approximation algorithm. However, CLICA has a limitation of only considering the probable interfering edges, not the actual interfering edges. Besides, it does not model all available radios altogether. Consequently, it has to execute an extra step to assign channels to additionally available radios after the first step. In addition, its local greedy choice during the channel assignment may trap a local optima. Moreover, it totally ignores external interference, traffic load, queuing delay, and environmental effects.

\(^1\)We further elaborate on the underlying methods in Section V.
B. Multi-Radio Breadth First Search based Channel Assignment (MRBFS-CA)

MRBFS-CA [4] is a centralized and semi-dynamic channel assignment technique for multi-radio WMNs. Here, a Channel Assignment Server (CAS) acts as the central entity. It periodically determines the channel assignment over the network and informs other nodes regarding the assignment. Before each assignment, the CAS collects interference estimates from all mesh nodes. In accordance with these estimates, CAS uses the Protocol Interference Model having the assumption of interference range as two times the transmission range. The estimates are used to assign channels to two different types of radio - default and non-default radios. CAS chooses a channel for the default radio such that use of the default channel in a WMN minimizes interference between the WMN and nearby networks. In the channel assignment procedure for the non-default radios, CAS generates a Multi-radio Conflict Graph (MCG) and uses a BFS-based channel assignment algorithm over the MCG. It prioritizes the radios based on the distance from CAS in terms of hop count and Expected Transmission Time (ETT) [80].

MRBFS-CA ensures connectivity using the default channel while minimizing interference during assigning channels to non-default radios. It separately considers each radio of a mesh node in the MCG. Therefore, channels can be optimally assigned to each radio. Moreover, it incorporates the impact of bandwidth and data rate along with all types of interference by using ETT during the channel assignment. However, it demands beacon messages from all mesh nodes and broadcasting from the CAS, which incur high control overheads. Moreover, the requirement of transmissions of the beacon messages limits the scalability of this technique. Besides, it completely ignores the queuing delay at the mesh nodes. Finally, there is no worst-case or best-case bound on the performance of the proposed channel assignment technique.

C. Traffic-Aware Routing-Independent Channel Assignment (TARICA)

TARICA [18] is a centralized and static technique to assign channels to multi-radio WMN links. TARICA has two phases - initial channel setting and iterative improvement. In the initial channel setting phase, a connectivity graph is decomposed into sub-graphs using BFS. This phase assigns distinct channels to the links in each sub-graph. This assignment results in some bottleneck links with high interference. In the iterative improvement phase, TARICA picks one of the bottleneck links at a time and greedily updates its channel to the least-used channel around it. The greedy assignment attempts to lower the extent of interference experienced by the link.

TARICA minimizes interference over the bottleneck links to maximize channel utilities of these links. However, it does not guarantee connectivity in a WMN as the minimizing process follows a greedy method. Besides, the assignment of the same channel to the links of a sub-graph in its initial channel settings results in high interference over these links. Therefore, consideration of only the bottleneck links in the iterative improvement phase may not generate an efficient channel assignment. Nevertheless, its greedy channel adjustment in the iterative improvement phase may trap a local optima due to the consideration of each bottleneck link at a time. In addition, it ignores external interference, queuing delay, and environmental effects during the channel assignment.

D. Topology-controlled Interference-aware Channel Assignment (TICA)

TICA [111] is a centralized and quasi-static technique for assigning channels to multi-radio WMNs. It executes a topology control scheme during the startup phase to facilitate the assignment. In this phase, at first, TICA builds a network connectivity graph by selecting the nearest neighbor for each node in the network. The objective is to obtain a topology considering the notion of power control to minimize interference among mesh nodes. Besides, it facilitates enhancing spectrum reuse in addition to ensuring network connectivity. Then, a centralized gateway builds a Shortest Path Tree (SPT) based on the connectivity graph. The path selection metric used for building the SPT is minimum power. Next to that, the gateway calculates the rank of each link in the Minimum Power SPT (MPSPT) based on the number of nodes that use a particular link to reach the gateway. In case of links with the same rank, link, whose power between the farthest node and the gateway is smallest, is given a higher rank. Subsequently, in the second phase, TICA assigns a channel to each link of the MPSPT according to its rank. It uses the essence of edge coloring for assigning channels to the links by minimizing co-channel interference.

An improved version of TICA, Enhanced TICA (e-TICA) is also proposed [111] to encounter the hidden link problem, resulting in a more accurate and fair channel assignment. Another version of e-TICA [111] employs a Minimum Spanning Tree (MST) rooted at the gateway, instead of a SPT that is employed in TICA and e-TICA, to reduce conflict among the channels. This approach improves medium access fairness among the mesh nodes, which in turn results in an improvement in network throughput. However, scalability remains a major issue as both the graph coloring and MST problems are NP-complete. Besides, in both TICA and its improved versions, external interference, traffic load, queuing delay, and environmental effects are completely ignored.

In addition to these techniques, there are some other graph based channel assignment schemes for multi-radio WMNs. For example, Sub-graph List Coloring (SLC) [2] creates sub-graphs of a multi-channel conflict graph for each of the available channels and assigns channels in each sub-graph starting from the lowest degree vertex in the sub-graph. Besides, a static technique named MSITD [112] designs a logical network topology with k-connected constraint and then performs channel assignment using MST search. It, first, develops a k-connected logical topology based on shortest disjoint paths and minimum-interference disjoint paths for each node-pair. Then, it reduces the channel assignment problem to an optimization problem, which attempts to maximize the network capacity. Finally, according to the logical topology, it finds the optimal CA solution using MST search algorithm.
Additionally, Polynomial Time Approximation Algorithm (PTAS) [6] finds a Maximum Independent Set (MIS) of an Overlapping Double Disk (ODD) graph by simultaneously activating the largest number of links while minimizing interference in a multi-radio WMN. Nonetheless, MCI-CA [14] assigns channels to independent sets of links in a WMN by partitioning the conflict graph using the Matroid Cardinality Intersection (MCI) [70] algorithm. It is motivated by the fact that a stable distributed link scheduling algorithm can avoid interference within a sub-network obtained by network partitioning. MCI-CA proves that satisfaction of Overall Local Pooling (OLoP) [68] by a sub-network is sufficient for a distributed maximal weight algorithm to be a stable link scheduling algorithm. It also proves that the conflict graph of a tree-shaped network satisfies OLoP under Primary Interference Constraint. Modified MCI-CA [15] extends MCI to support the Protocol Interference Constraint with the help of the Lehot-D [71] algorithm.

Now, we focus on mathematical formulation-based approaches. A number of techniques falling into this group exploits different forms of Integer Linear Programming (ILP). For example, an ILP-based channel assignment technique [12] minimizes the maximum total flow for each available channel in a Wireless-Optical Broadband Access Network (WOBAN) maintaining some constraints. Besides, ILP with Lagrangian Relaxation [11] minimizes the total interfering load in a multi-radio WMN. In addition, Collision Domain Size based channel assignment [13] minimizes the average and maximum collision domain size in a multi-radio WMN using ILP formulation. Furthermore, another approach [36] formulates the joint routing, channel assignment, and rate allocation problem as a Mixed-Integer Non-Linear Problem (MINLP) with the objective to find the best combination of route selection, channel assignment, and rate allocation decisions while achieving proportional fairness. Nevertheless, Semidefinite Programming (SDP) [9] based channel assignment solves the MAX k-CUT problem on a conflict graph using a relaxed formulation that can be solved in polynomial time. This technique is enhanced in ISDP, which is described below.

E. Integer Semidefinite Programming (ISDP) based channel assignment

ISDP [16] based channel assignment is a centralized and static technique for assigning channels to multi-radio WMN links. Its problem formulation resembles that of SDP [9] based technique. The main difference in this formulation is the introduction of a new local interface constraint in addition to the original constraint in SDP. ISDP proves that combination of these constraints provides a tighter bound on the achieved solution. The solution of a relaxed ISDP formulation is optimal but not guaranteed to be feasible. Therefore, three rounding algorithms are proposed to obtain the feasible solution - SDP-COLORSET, SDP-GREEDY, and SDP-SKELETON. All of these algorithms impose interface constraint by randomly choosing channels for a node from the outcome of ISDP such that the number of chosen channels is less than or equal to the number of available interfaces of that node. The first two algorithms, SDP-COLORSET and SDP-GREEDY, select a common channel for two end nodes of a link. SDP-COLORSET randomly selects the channel, whereas SDP-GREEDY selects the channel from all possible options according to ISDP such that the channel diversity is maximized. None of these two algorithms ensures connectivity, as their channel assignments do not follow any distinct sequence. Only SDP-SKELETON guarantees connectivity by constructing a spanning tree of the connectivity graph and then assigning channels following BFS with an arbitrary root node. Channel assignment in SDP-SKELETON also maximizes channel diversity in the same way as SDP-GREEDY. All of these algorithms drop an edge if they do not find any common channel of the end nodes.

ISDP based techniques attempt to increase the overall network performance by allowing more simultaneous transmissions maintaining network connectivity with the help of a spanning tree of the connectivity graph. However, this technique only considers orthogonal channels and ignores external interference, traffic load, and environmental effects.

F. Superimposed Code based channel assignment

Superimposed code based channel assignment [26] is a distributed technique to assign channels to multi-radio WMN links. It may be either static or dynamic in nature. It assigns a source node to each link prior to the assignment. This technique utilizes a special kind of superimposed code called an s-disjunct code to minimize interference. The s-disjunct code contains a number of codewords and guarantees that the boolean sum of any s code words is not contained within the code. Each node maintains an s-disjunct code in a matrix form that indicates channel usage in neighborhood interferer nodes. Each column in an s-disjunct code corresponds to an interferer node and each row corresponds to a channel. Construction of an s-disjunct code starts by classifying all available channels of a node in two categories - primary and secondary. Currently-used channels are categorized as primary channels and contain 1s in an s-disjunct code. Currently-free channels are categorized as secondary channels and contain 0s in a s-disjunct code.

Two flexible localized channel assignment algorithms exploit the s-disjunct code. In the first channel assignment algorithm, the source node of a link attempts to assign a channel to the link by finding a set of its own primary channels that are secondary to all of its neighbors. If the node finds an empty set, then it tries to find a set of its own secondary channels that are secondary to all its neighbors. If the node again finds an empty set, it selects its primary channels by choosing the least row weight in its neighbors. In the second channel assignment algorithm, the source node of a link attempts to assign a channel to the link by finding a set of its primary channels that are secondary to the destination node and all of the neighbors of the destination except the source node. If the node finds an empty set, then it tries to find a set of its own secondary channels that are secondary to all its neighbors but primary to at least one of the neighbors of the
destination node. If the node again finds an empty set, then it selects one of its own primary channels that is secondary to the destination node.

This technique minimizes switching delay by choosing channels from a small subset of primary channels while maintaining connectivity. Besides, it requires information from only two hop neighbors and thus incurs low control message overhead. Moreover, it can guarantee the lowest interfering transmissions in sparsely deployed WMNs. However, it does not consider non-orthogonal channels, external interference, traffic load, and environmental effects. Moreover, it experiences a ripple effect as assignment of a currently unused channel makes it primary and freeing a currently used channel makes it secondary, which may be required to be propagated through a long path in a WMN.

In addition to these techniques, there are some other mathematical formulation-based channel assignment techniques for multi-radio WMNs. For example, the technique proposed in [143] uses an auction-based scheme for joint random network coding, channel assignment, and broadcast link scheduling problem. At first, it formulates the problem using linear optimization aiming for throughput maximization in network-coded multi-radio WMNs. Then, based on this formulation, it further formulates the channel assignment and broadcast link scheduling problem as a two-sided multi-assignment problem. Subsequently, it converts the multi-assignment problem to a minimum cost flow problem. Then, it uses the dual of this problem as a platform for auction-based optimization algorithm. Besides, another technique [144] designs a joint optimization model for channel assignment and multicast tree construction in multi-radio WMNs. This model follows a cross-layer mathematical formulation based on a Binary Integer Programming (BIP). The channel assignment sub-problem of this model attempts to minimize total network interference in addition to addressing the hidden channel problem [7].

Now, we focus on AI based techniques. We mainly describe the channel assignment techniques based on genetic algorithm and Tabu search. Additionally, there is a Q-learning [75], [76], [140] based technique [1] for mobile sensor networks that can also be utilized in a WMN with mobile clients.

G. Genetic Algorithm (GA) based channel assignment

Genetic Algorithm (GA) is a population based stochastic search method. GA based channel assignment [11] is a centralized and static technique for assigning channels to WMN links. This technique attempts to minimize total interfering traffic load over the network. This technique adopts a special representation of individuals for channel assignment. Here, each gene represents an assigned channel for a WMN link in the representation of an individual. The technique exploits random selection, crossover, and mutation with the individuals in all iterations. Roulette wheel selection is used as the selection method. Crossover operation takes two different parents - primary and secondary. The portion obtained from primary parent is completely maintained in offspring. However, genes from secondary parent is attempted to maintain as much as possible while ensuring feasibility. Mutation switches the channel of a randomly chosen link to a randomly-chosen feasible channel.

This technique attempts to minimize total interference over the network with avoidance of local optima using mutation operator. However, this technique does not have any objective function to maintain network connectivity. Therefore, the resultant channel assignment may lose connectivity. Moreover, it does not consider external interference, traffic load, and environmental effect.

H. Non-dominated Sorting Genetic Algorithm -II (NSGA-II) based channel assignment

The Non-dominated Sorting Genetic Algorithm (NSGA) [72] is a variant of the Multi Objective Evolutionary Algorithm (MOEA) [73]. The underlying method of NSGA follows Pareto ranking and fitness sharing. The main disadvantages of NSGA are cubic computational complexity, premature convergence, and the need for specifying a sharing parameter. The Non-dominated Sorting-based Genetic Algorithm II (NSGA-II) [74] alleviates all these disadvantages of NSGA.

NSGA-II based channel assignment [8] is a centralized and quasi-static technique for assigning channels to WMN links. This technique attempts to optimize two objective functions subject to two constraints. Optimization of the objective functions involves maximization of network connectivity and minimization of network interference. Two constraints are imposed on the maximum number of active radios in a node and the maximum number of active channels on a link. This technique adopts a genetic representation in which each gene represents a channel state (on or off) in the representation. It utilizes the tournament selection method, as this method is compatible with the ranking-based fitness function that is used by NSGA. It uses a circular two-point crossover with a deletion operator as the recombination operator. For mutation, it exploits inversion variation based methods.

Another NSGA-II based scheme [46] follows similar operators and parameter values as [8] and attempts to optimize a joint channel assignment and multicast routing problem in multi-radio WMNs. NSGA-II based channel assignment techniques ensure connectivity while exhibiting very fast convergence (quadratic) rate with guaranteed escape from a local minima. However, these techniques ignore the existence of non-overlapping channels, external interference, traffic load, and environmental effects.
that considers a discrete search space and aims at finding the minimum interference channel assignment decision having topology preservation [126]. DPSO-CA exploits a synergy between the search strategies of a basic PSO algorithm and genetic operations such as crossover and mutation in order to ensure optimality.

Another channel assignment scheme, based on Improved Gravitational Search Algorithm (IGSA) [127], extends the concept of DPSO-CA algorithm. The Gravitational Search Algorithm (GSA) is a variant of PSO, where particles are considered as collection of masses, which interact with each other based on the Newtonian gravity and the laws of motion. IGSA introduces a local search based operator to improve the performance of basic GSA by enhancing its exploration capabilities. IGSA based channel assignment, similar to DPSO-CA, aims at minimizing the overall co-channel interference in addition to ensuring topology preservation.

Both DPSO-CA and IGSA are centralized and static techniques, which achieve good network throughput through minimizing interference while preserving the original topology. However, these approaches are designed for networks with unified traffic load only. Moreover, these techniques ignore external interference, queuing delay, and environmental effects.

J. Generic Tabu Search (GTS) based channel assignment

GTS based channel assignment [21] is a centralized and static technique that probabilistically assigns channels to a Maximal Independent Set (MIS) of WMN links. This technique starts with some randomly selected channel assignments for a conflict graph. GTS improves the channel assignments through a number of iterations. Each of the iterations executes three phases. The first phase generates MISs for some randomly chosen channel assignments. The second phase combines the MISs to generate a partial solution for the channel assignment. The third phase improves the partial solution while maintaining the interface constraints. This phase mainly performs tabu search, which executes a local search by exploring random neighboring solutions. An improved neighboring solution is stored in a limited size central memory along with old ones. Besides, similar to this phase, another technique [9] also uses Tabu search for the channel assignment. In addition, an improved tabu search-based technique [22] incorporates handoff and traffic load variation parameters in its objective function. This improved optimization model facilitates achieving more optimized channel assignment decisions.

This technique utilizes a local search and stores old channel assignments along with the newly found best one. This storing approach guarantees not to trap a local optima. However, this technique does not take any measure to maintain the network connectivity. Moreover, it does not consider non-orthogonal channels, external interference, traffic load, and environmental effects.

K. Q-Learning based channel assignment

Q-Learning based channel assignment [1] is a distributed and dynamic approach to activate channels in multi-radio mobile sensor networks. It utilizes reinforcement technique [75] which enables agents to continuously take decisions based on the experience in an unknown environment. The technique also periodically explores new and random operating points, which do not come from the experience. A matrix called $Q$-matrix represents the experience. Each decision is evaluated by updating the matrix with some reward that reflects accuracy of the decision.

This technique was proposed for sensor networks to improve energy efficiency. Therefore, accuracy of decision is determined on the basis of energy efficiency. However, we can also use the same technique to assign channel to links of a WMN with unknown characteristics. Here, we only need to change the basis of accuracy of channel assignment decision from energy efficiency to our desired objective function such as interference minimization, throughput maximization, etc. We can further improve the technique through exploiting a modified efficient version of Q-Learning called delayed Q-Learning [76].

The main strength of this distributed approach is its capability of escaping from local optima through exploring a random action. Such exploration is very rare in distributed approaches of channel assignment used in WMNs. In addition, it can also achieve effective channel assignment for mobile clients due to its adaptive nature. However, it is difficult to ensure continuous connectivity in this type of learning technique as individual decision at each node cannot guarantee to preserve overall network connectivity. In addition, this technique uses some parameters and efficient tuning of these parameters may raise difficulties during its deployment.

L. Adaptive Dynamic Channel Allocation (ADCA)

ADCA [69] is a dynamic channel assignment scheme that considers a hybrid multi-radio WMN architecture. It is an optimization algorithm that considers both throughput and delay for channel assignment with an objective to reduce packet delay without degrading the network throughput [50].

In the hybrid architecture, each mesh node has both static and dynamic interfaces. The dynamic interfaces of each mesh node are able to switch channels when needed, whereas, the static interfaces use fixed channels for transmission. ADCA uses a heuristic channel assignment scheme for static interfaces that aims at maximizing the throughput from end-users to gateways. On the other hand, dynamic interfaces work in an on-demand fashion, where two dynamic interfaces negotiate for a common channel. Each dynamic interface maintains multiple queues in the link layer with one queue for each neighbor. The data to be sent to each neighbor are buffered in the corresponding queue. Each node performs a two-step channel negotiation. In the first step, it performs a priority-based neighbor selection. ADCA evaluates the priority of a neighbor by considering both its queue length and the waiting time in the queue. Based on the queue length, ADCA decides on whether it will perform the second step of channel negotiation. If the queue length is over a predefined threshold, it assumes that the traffic load may have been saturated, indicating that further channel negotiation will not be effective.
ADCA can negotiate common channels among more than two nodes at each interval, which results in reduced packet delay. Besides, the consideration of both throughput and delay facilitates reducing delay without sacrificing throughput. However, ADCA is only suited for multi-radio WMNs with hybrid architecture (i.e., mesh nodes having both static and dynamic interfaces). Besides, it has limited effectiveness in case of saturated traffic loads. In addition, it ignores external interference and environmental effects.

In addition to these techniques, there are some other AI-based channel assignment techniques for multi-radio WMNs. For example, [148] uses an unified priced-based framework for congestion control and channel assignment. It is a quasi-static scheme that follows a decoupling approach by first performing routing and an initial channel assignment, and then jointly conducting congestion control and channel reassignment. It considers throughput with different fairness objectives such as proportional fairness and maxmin fairness as the optimization criteria. Besides, another technique [149] introduces a simulated annealing-based joint multicast routing and channel assignment aiming to find a delay-bounded low cost multicast tree and minimum interference channel assignment decision. Additionally, another study [150] uses a stochastic local search-based scheme to find minimum interference channel assignment decision. In addition, there are other techniques based on different optimization models [22], [136], [151], [152], learning automata [153], etc., as well.

Now, we briefly elaborate some important peer-oriented channel assignment techniques. We omit some peer-oriented techniques [10], [11] in the elaboration as they use three-way handshaking and thus incur very high control overhead.

### M. Probabilistic Channel Usage based channel assignment

Probabilistic Channel Usage based channel assignment [29] is a peer-oriented, distributed, and dynamic approach for assigning channels to interfaces in a multi-channel multi-interface Ad-Hoc wireless networks. This technique proposes separate queues for each of the available channels and categorizes the available channels of a node into two subsets — fixed and switchable. A node receives data using the fixed interfaces while transmitting data using the switchable interfaces after tuning them to the fixed interfaces of destination nodes. Channel assignments to the fixed interfaces last longer compared to the switchable interfaces. These considerations in this technique enable it to be used in multi-radio WMNs as a dynamic channel assignment approach.

The channel assignment technique uses two different approaches to assign channels to the fixed and switchable interfaces. A node starts its operation with random channels in all of its interfaces. It periodically changes the channel of its fixed interface to a less-used channel with some probability if the number of users on the same fixed channel gets larger. To understand whether the number of users on the same fixed channel gets larger or not, the technique periodically exchanges its channel usage list and always maintains a channel usage list of neighbor nodes. On the other hand, the channel assignment to a switchable interface depends on the oldest packet in its queue. A switchable interface transmits at most a certain number of packets or stays at most a certain amount of time on a channel before switching to another channel.

This technique ensures connectivity by using switchable interfaces. It allows fixed interfaces to operate on distinct channels for longer intervals, resulting in a low channel switching delay. On the other hand, it ensures the switching of the switchable interfaces to channels with least recently generated data after a certain interval or a certain number of packet transmissions, resulting in fairness to all interfaces. This combination of two different strategies achieves a delicate trade-off between channel switching delay and fairness. The constraint on channel switching also provide safeguards for channel oscillation. Besides, this technique assigns channels with only locally available information without any synchronization. Moreover, the considerations of dynamic traffic patterns and neighborhood broadcasting enable this technique to support mobile clients. However, this technique does not consider any interference cost during channel assignment to the switchable interfaces. Therefore, throughput of the network is not optimized. Moreover, it does not consider external interference and environmental effects.

### N. Hyacinth

Hyacinth [31] is an architecture for routing and channel assignment in multi-channel WMNs having a wired gateway. The architecture imposes higher priorities on the nodes in proximity to the wired gateway. The channel assignment technique, used for this priority-based architecture, is a peer-oriented, distributed, and semi-dynamic approach using already established routing decisions. It utilizes information from $(k+1)$ hop neighbors, where $k$ is the ratio between interference and communication ranges and is typically in the range of 2 to 3. This technique uses cross-section goodput as its evaluation metric.

Hyacinth starts with taking routing decisions based on three metrics - hop count, gateway link capacity, and path capacity. Then channel assignment performs neighbor-interface binding based on these routing decisions. Interfaces are distinguished in two categories during the channel assignment to avoid instability during the neighbor-interface binding. Interfaces that communicate with parent nodes in different routes are distinguished as UP-NICs, and interfaces that communicate with children nodes in different routes are distinguished as DOWN-NICs. Only parent nodes can assign channels to their DOWN-NICs. Channel assignment starts from the highest priority node and then follows the priorities of other nodes in the subsequent assignments. Hyacinth periodically assigns an interface to a channel with the lowest total load. The total load is calculated as a weighted sum of the number of nodes using the channel with aggregated traffic load as their weights. Each node periodically exchanges its channel usage information to $(k+1)$ hop neighbor nodes to ensure availability of the information required in the calculation of total load. After deciding on changing the channel on an interface, a parent node transmits the information about the newly changed
channel only to the corresponding child node. In the case of a node failure, child node attempts to connect to an already known alternate parent node.

This technique avoids the ripple effect by distinguishing a NIC as either UP-NIC or DOWN-NIC. Besides, it reduces control message overhead by using IP multicasting to send information to \((k+1)\) hop neighbor nodes in place of broadcasting. Moreover, it guarantees fast failure recovery by quickly establishing a connection to an already known alternate parent node in the case of a node failure. However, the stored information about the alternate parent nodes may not be consistent with the current network status. Therefore, this technique may use stale data during a failure recovery. On the other hand, multiple neighboring nodes may choose the same channel at the same time, assuming the channel as the least loaded one. However, assignments by multiple nodes may increase the total load on the selected channel, and thus the already made decision may not be the optimal one any more. Thus, this technique may face an oscillation during the channel assignment. Additionally, it does not take any measure to ensure network connectivity. Moreover, it ignores external interference and environmental effects.

**O. Skeleton Assisted partition FrEe (SAFE)**

SAFE [19] is a peer-oriented, distributed, and dynamic technique to assign channels to links of multi-radio wireless networks. SAFE assigns channels using two different approaches following two different conditions on the number of available channels and interfaces. If the number of available channels is less than two times the number of available interfaces, then SAFE randomly assigns channels to the links. Pigeonhole principle guarantees network connectivity for the random assignment under this condition. However, network connectivity may be disrupted by random assignment if the condition does not hold. Therefore, in the case of such violation of the condition, a skeleton or a spanning tree of the connectivity graph is created and all of its edges are retained during the channel assignment to ensure connectivity.

The skeleton-assisted approach dynamically assigns channels to each node. Channel assignment starts with selecting random channels for all interfaces except one. The remaining one is used to maintain connectivity by retaining an edge of the skeleton. This interface is assigned to a channel common to both of the end nodes. SAFE requires information about the channel usage at neighborhood nodes to determine the common channel. Therefore, each node broadcasts its channel usage both periodically and after each new assignment. In the case of unavailability of such a common channel, a default channel is used.

This approach guarantees network connectivity with only locally available information. Moreover, it adopts mobile clients by providing support for dynamically arriving and leaving clients using broadcasting of channel usage information both periodically and after any channel re-assignment. However, this broadcasting incurs high control message overhead. Besides, the random choices of channels used in SAFE may increase interference, resulting in poor network throughput. Moreover, the use of a default channel in the skeleton-assisted approach may increase interference. Finally, it does not consider external interference, traffic load, and environmental effects.

**P. Joint Optimal Channel Assignment and Congestion Control (JOCAC)**

JOCAC [20] is a peer-oriented and semi-dynamic technique used to assign channels to multi-channel WMN links by following either a centralized or a distributed approach. In the centralized approach, a central gateway assigns channels to WMN links. In the distributed approach, each node performs channel assignment to some distinct links with the help of periodically-broadcasted channel usage information from neighbor nodes.

This technique attempts to formulate interference following the Physical Interference Model and then minimizes it. The minimization of interference is realized by optimizing the notion of congestion control. Congestion control refers to the maximization of aggregated utility across all sources subject to link capacity constraint. The optimization of congestion control is mapped to the channel assignment problem using lagrangian multipliers. The channel assignment problem in turn refers to the maximization of the sum of link capacities. The channel assignment problem is finally reduced to an interference minimization problem by incorporating signal to interference noise ratio (SINR).

This technique considers the actually received power to capture interference in the network. This approach of interference prediction is practical for most of the WMNs. Moreover, it considers noise by incorporating SINR in its formulation of the objective function. Besides, this technique supports non-orthogonal channels and ensures stability by assigning a channel to each link from only one of the end nodes. On the other hand, this technique does not consider connectivity in its objective function. Therefore, connectivity is not guaranteed after the final channel assignment.

**Q. Two-hop clustering based channel assignment**

Two-hop clustering based channel assignment [32] is a peer-oriented distributed technique to assign channels in multi-radio WMNs. This technique sets up a DEFAULT interface in each mesh node at the beginning. Then it executes three phases - the clustering phase, the inter-cluster static channel assignment phase, and the intra-cluster channel assignment phase. The clustering phase partitions a WMN into some clusters following the Max-Min \(D\)-cluster algorithm [77]. In each cluster, a node is either a cluster head or a cluster member, and each cluster member can be at most \(D\) hops away from its cluster head. \(D\) is chosen to be \(2\) for the clustering in this channel assignment technique. The inter-cluster static channel assignment phase assigns a FIXED channel to all members in a cluster using a distributed greedy algorithm and a DEFAULT channel to gateway nodes within the same cluster to preserve connectivity with other clusters. The choice of the FIXED channel is achieved by a conflict-avoiding algorithm that enables each cluster head to choose a free
channel that is not used by any of its neighborhood cluster heads. The cluster head chooses the least conflicting channel in the case of unavailability of such channel. Intra-cluster dynamic channel assignment assigns DYNAMIC channels to all nodes. DYNAMIC channels are chosen based on the free time percentages of all available channels. Cluster heads periodically broadcast estimations of free time percentages of all available channels to all cluster members. The estimation is obtained from promiscuous listening by an idle interface of a node selected by the cluster head. DYNAMIC channels are assigned using the estimation following two switching methods - Greedy Switching and On-demand Switching. Greedy Switching simply chooses the channel with maximum free time percentage. On the other hand, On-demand Switching attempts to switch DYNAMIC channels if their free time percentages drop to a certain threshold. The switching is executed by two-way handshaking with the neighbor nodes.

This technique ensures connectivity using the FIXED channel within a cluster and using the DEFAULT channels among different clusters. It switches DYNAMIC interfaces based on the free time percentage, which depends on both interference and data traffic on WMN links. Therefore, this technique provides interference minimization as well as load balancing by the switching of DYNAMIC interfaces. Additionally, it minimizes broadcasting overheads by enabling control message broadcasting only from a cluster head to its cluster members. Moreover, it minimizes the control overheads by promiscuous listening. On the other hand, use of the fixed common channels may increase interference in a cluster. Besides, connectivity among the clusters may be disrupted in the case of a failure of any gateway node, as the technique does not take any measure to adapt to the failure. Nonetheless, it ignores the impact of channel switching delay during the On-demand Switching of DYNAMIC interfaces.

Now, we briefly describe some important greedy approaches for channel assignment that cannot be classified in any of the previously mentioned categories.

R. Cluster-based Multipath Topology control and Channel assignment scheme (CoMTaC)

CoMTaC [25] is a semi-dynamic approach to assign channels in multi-radio WMNs. CoMTaC executes a two-step topology control scheme during the startup to facilitate the channel assignment. The first step constructs clusters of a fixed radius in terms of hop count. All nodes within a cluster are assigned to a common channel to ensure intra-cluster connectivity. Nodes, which are neighbors to multiple clusters, tune their second interfaces to a common channel that is used in the highest priority cluster to ensure inter-cluster connectivity. The second step constructs a spanner of the connectivity graph. The spanner removes high interference paths and may contain multiple paths between any two nodes to help identify multiple feasible paths using non-default interfaces. Therefore, CoMTaC prefers the spanner over a MST.

CoMTaC uses the outcome of the topology control in its channel assignment process. It assigns channels to default and non-default interfaces in two different ways using two different local interference estimation processes. CoMTaC primarily focuses on external interference for assigning channels to the default interfaces. It uses a weighted sum of channel utilization and channel quality as the metric during the assignment. Channel utilization is obtained from the packets captured by periodically configured non-default interfaces. Channel quality is obtained from a number of lower-layer metrics such as bit or frame error rate, received signal strength, etc. On the other hand, CoMTaC focuses on all interferences experienced within a cluster for assigning channels to non-default interfaces. It uses average link layer queue length as the metric reflecting the interference. The average link layer queue length is calculated by multiplying the I-factor [78], channel usages, and queuing delay. Here, the I-factor is used to support partially overlapping channels. Next, a cluster head determines the channel assignments based on the metric and also distributes the assignments in its cluster. All cluster members periodically transmit their channel usages and averages of their queue lengths to their corresponding cluster head to assist the channel assignment process. Boarder nodes also transmit the same information to cluster heads of neighboring connected clusters.

This technique ensures connectivity using a default interface within a cluster and by border nodes among different clusters. Besides, CoMTaC minimizes the overhead cost by broadcasting only over the default interfaces within a cluster and over the non-default interfaces of the border nodes across the clusters. In addition, it provides fault tolerance by constructing multiple paths. Moreover, it considers partially overlapped channels, external interference, queuing delay, and environmental effects. Finally, it avoids channel oscillation by topology control and avoids ripple effect byassigning channels only from the cluster heads. However, the use of a default channel in this technique increases intra-cluster interference.

S. Neighbor Partitioning and Load Aware channel assignment

The Neighbor Partitioning approach [28] is a centralized and static channel assignment technique for multi-channel WMNs. This technique executes in two steps considering the constraints on the number of available channels, the number of available interfaces, and channel capacity. In the first step, a node groups its neighbors such that the number of the groups equals the number of available interfaces on that node. Subsequently, the next node also groups its neighbors following the same process and maintaining the grouping of the previous node as a constraint. All nodes do the same grouping one after another. Finally, in the second step, each group is assigned a channel, which is the least used in neighbor nodes. This channel assignment completely ignores traffic load in WMNs.

Load Aware channel assignment [28] considers the estimated traffic load by jointly performing channel assignment and routing in two phases - the exploration phase and convergence phase. The technique begins with a greedy channel assignment to all links according to the non-increasing order of link criticality, which is the expected traffic load of a link. This channel assignment minimizes the degree of interference,
which is calculated as the total expected interfering load within an interference region. The assigned channels are maintained by the routing algorithm, which executes just after the channel assignment. These two steps are iterated for a number of times in the exploration phase. The technique enters into the convergence phase each time it finds a better cross-section goodput. The convergence phase follows the same steps as the exploration phase, except it confines its re-routing to the flows that exhibit non-conformance between the expected traffic load and the capacity of the assigned channel. These steps are repeated until the phase converges or no better configuration is found in several iterations. The convergence phase again enters in an exploration phase in the case of a non-feasible output. The technique terminates if the convergence phase provides a feasible output.

This technique ensures connectivity while minimizing interference over a WMN. However, it considers only potential interference, which may significantly differ from the actual interference in many cases. Moreover, it does not consider external interference and environmental effects. Additionally, Load Aware channel assignment may exhibit very slow convergence in the case of a network with a higher number of cross links.

T. Routing, Channel assignment and Link scheduling (RCL)

RCL [30] is a centralized and static technique for multi-radio WMNs. This technique utilizes a new representation of the connectivity graph called a flow graph. A flow graph contains a universal source node and a universal sink node. The universal source node has directed edges to all nodes with outgoing flow. Each gateway node, which is used to communicate with a wired router, has an infinity capacity directed edge to the universal sink node. A flow graph contains a copy of each node for each available channel in the network. All copies of a node for different channels are connected by infinite capacity edges to imply constraint-free communication within a node. Each of the other edges in the flow graph represents transmissions on a distinct channel. This type of edge is assigned with a capacity that reflects the required capacity pertinent to the traffic load over the link maintaining the channel capacity.

The flow graph is obtained after the routing decisions. Channel assignment takes a flow graph, interface constraint, and link capacity constraint as its inputs. The flow graph is guaranteed to maintain the channel capacity constraint but may violate the interface constraint. Channel assignment techniques remove this violation from the flow graph as well as minimize the potential interference over the network. The channel assignment technique follows three phases. In the first phase, the technique splits each mesh node such that each node maintains the interface constraint and link capacity constraint. In the second phase, the technique assigns channels such that the number of connected components for each available channel is maximized and the intra-component interference is minimized. This step considers first $I$ channels during the channel assignment to a node interface where $I$ is the number of interfaces on that node. In the third phase, the technique improves channel diversity by considering all of the available channels in the network. If the number of connected components in the flow graph, obtained from second phase, is less than or equal to the number of available channels, then the technique retains the already assigned channel to each of the connected components. If the condition between the number of connected components and the number of available channels does not hold, the technique merges nodes of the flow graph following a greedy approach to ensure the condition before assigning a channel. For all possible merging options, it determines a metric for each of the available channels - the maximum interference among all connected components having the same channel. The merging process chooses the option that minimizes the increase in this metric maintaining the interface constraint.

This technique provides a certain performance bound ensuring connectivity without any heuristic. Moreover, it considers the expected traffic load of each link while minimizing interference. On the other hand, the metric considered in the greedy merging process does not reflect the overall decrease in network interference. Besides, it does not consider non-orthogonal channels, external interference, and environmental effects.

U. Maxflow-based Centralized Channel Assignment Algorithm (MCCA)

MCCA [23] is a centralized and static technique to assign channels in multi-radio WMNs having gateway nodes that are connected to wired networks. This technique formulates the maximization of throughput as a single commodity flow problem. The formulation considers a new graph representation of a connectivity graph. The graph contains a universal source node, a universal sink node, and edges of infinite capacity connecting all other nodes to those two nodes in addition to original nodes and edges in the connectivity graph. MCCA assigns channels to the edges of this graph in two phases - link-group binding and group-channel assignment. In the first phase, MCCA groups the links of each node based on their local flow, which implies the link criticality. This phase maintains interface constraint on each node and merges groups, if required, to preserve the constraint. The merging process greedily merges two groups with the least total flow. In the second phase, MCCA sorts the groups and then assigns channels to them according to the sorted order. MCCA attempts to assign different channels to the groups containing potential interfering links.

This technique attempts to increase network throughput by minimizing interference among links with high local flow. In addition, it guarantees connectivity by assigning channels to all edges of the generated graph. Moreover, it exhibits a fast (quadratic) convergence rate. On the other hand, the prioritization of a group in this technique is based on link criticality, which focuses on the highest flow link in the group rather than the overall flow in the group. Therefore, the channel assignment following the prioritization may adversely affect the network throughput. Besides, it does not consider external interference and environmental effects.
V. Balanced Static Channel Assignment (BSCA) and Packing Dynamic Channel Assignment (PDCA)

BSCA [24] is a centralized and static technique to assign channels in multi-radio WMNs. It assigns channels to groups of links with constraints on the maximum number of active channels on a link, the maximum number of radio interfaces on a node, and the maximum number of active links in an interference region. It considers each group of links using the same constraint as a constraint set and attempts to balance the traffic load over all such sets. It starts with the calculation of total traffic loads over all channels on each link by solving a linear programming formulation using a primal-dual algorithm [79] and using the formulation during its channel assignment. Then, it executes an iterative process to assign channels to all links based on their current traffic loads. At the beginning of the iterative process, it sets current traffic loads over all channels on all links to zero. Then, it calculates the maximum traffic load over all constraint sets. BSCA picks the link having the minimum value among these calculated loads. It assigns a channel to a link in an iterative manner such that the maximum traffic load of all constraint sets is minimized. It updates the traffic loads of all constraint sets that correspond to a newly assigned channel.

On the other hand, PDCA [24] is a centralized and semi-dynamic technique to assign channels in multi-radio WMNs. It starts with a calculation of total traffic loads over all channels on each link by solving a linear programming formulation similar to BSCA and scale them by a large value to make them integral. PDCA aggregates all flows over different channels on a given link into a single scaled flow on that link. Here, the required data traffic of a flow may not be transmitted, satisfying the constraints on link capacity and node interface. In the case of a violation of any of the constraints, the maximum possible portion of the traffic load is transmitted with available resources, and the remaining portion of the traffic load has to wait. PDCA periodically assigns channels to links according to this remaining traffic load. It sorts all remaining traffic loads in a descending order at the start of each period. Then, it assigns the available channels, with capacities in descending order, to the links with remaining traffic loads maintaining their order.

Both BSCA and PDCA use a linear programming formulation that can flexibly incorporate different parameters, and thus they are suitable for WMNs with heterogeneous nodes. Moreover, both of them achieve load balancing. However, none of them considers interference, and thus they do not optimize network throughput. Besides, these techniques do not take any measure to ensure connectivity. Finally, they use synchronization, which requires a scheduling algorithm and thus incurs additional control overhead.

As the channel assignment techniques exhibit significant variation in their underlying methods, they also exhibit variation in the metrics they utilize for assigning channels. Next, we present the metrics used for assigning channels in the literature.

IV. Metrics for Assigning Channels

There are four principal components considered in channel assignment metrics - interference and channel diversity, capacity or data rate, throughput, and delay. Most of the channel assignment metrics consider interference and channel diversity to optimize their decisions through reducing interference in the network, as interference degrades network performance to the greatest extent. A number of studies [1], [2], [4], [5], [6], [8], [9], [10], [13], [15], [17], [20], [21], [25], [26], [27], [30], [31], [32] efficiently address both inter-flow and intra-flow interferences in their metrics. Many channel assignment metrics [4], [8], [9], [10], [11], [13], [14], [15], [16], [18], [20], [27], [29], [30], [32] attempt to minimize these interferences by maximizing channel diversity to achieve maximum performance in data transmissions. However, only few research studies [1], [4], [25] address external interference in their metrics.

Several channel assignment algorithms use capacity or data rate in their channel assignment metrics to guarantee load balancing in WMNs. Most of them use link capacity [9], [11], [12], [20], [24], [28], [30], [31] to evenly balance traffic load over the WMNs and a few of them use channel capacity [12], [18], [24], [25] for this purpose.

Besides, some channel assignment metrics exploit overall network throughput to maximize the total number of successful data transmissions over WMNs. Some of them use the actually achieved throughput [23], which is termed as goodput [28], [31] and a few of them use maximum end-to-end throughput of all flows [19] over a WMN.

Finally, a few channel assignment metrics utilize delays to ensure high-speed transmissions over WMNs. Some of them use the total end-to-end delay [4], [19]. Additionally, some centralized approaches [4] sort links based on the delay from the central gateway, at the pre-processing step and ensure high priorities to the links close to a central gateway. However, none of them separately considers queuing delay or channel switching delay. Only a few approaches explicitly consider queuing delay [25], [29] and channel switching delay [29] in their metrics.

Metrics used in channel assignment in multi-radio WMNs share one or more of these four components. Most of the channel assignment algorithms in multi-radio WMNs exploit their own metrics. However, many of these metrics share the same inherent essence while being represented in different ways. We categorize the metrics based on the underlying essence in the following manner -

1) Total number of interfering links in the network: This metric is based on the principal component interference and channel diversity. It counts the total number of interfering links in a WMN. A link is assumed to be interfering if it is assigned to a channel and the same channel is also assigned to one or more links within the interference region of that link. This metric indicates the global impact of a certain channel assignment. Many approaches [8], [9], [16], [17], [18], [21] use this metric with the interference region obtained using the Primary
2) Total channel interference cost within interference range: This metric is also based on the principal component interference and channel diversity. It calculates the cost of all interfering links within the interference region of a particular link. The cost of interfering links may be of varying types, for example linear cost function [10] and total fraction of interfering flows [30]. This metric indicates the local impact of a certain channel assignment. Some approaches [10], [30] use this metric and attempt to minimize the cost. These approaches consider the interference region using the Protocol Interference Model.

3) Total interfering load in the network: This metric is also based on the principal component interference and channel diversity. It calculates the sum of traffic loads over all interfering links in a WMN. This metric indicates the global impact of a certain channel assignment. One approach [11] uses this metric. This approach obtains the interference region following the Protocol Interference Model.

4) Size of co-channel interference set: This metric is also based on the principal component interference and channel diversity. Here, the co-channel interference set of a particular link is defined as a set of links that interfere with that link. This metric indicates the local impact of a certain channel assignment. One approach [13] exploits this metric through utilizing both the average and maximum size of the co-channel interference set. This approach obtains the interference region following the Primary Interference Constraint. Another approach [27] exploits this metric through utilizing only the maximum size of the co-channel interference set within an interference region following the Protocol Interference Model.

5) Sum of end-to-end throughput: This metric is based on the principal component throughput. It calculates the sum of the end-to-end throughput of all existing flows in a WMN. This metric indicates the global impact of a certain channel assignment. One approach [19] uses this metric to guarantee fairness over all flows in a WMN.

6) Cross-section goodput: This metric is also based on the principal component throughput. It calculates the sum of actually achievable throughput in a WMN. This metric indicates the global impact of a certain channel assignment. One approach [28] uses this metric to maximize the sum of throughput between all pairs of nodes in the network. Another approach [31] uses this metric to maximize the sum of throughput over all pairs between a normal node and a gateway node in the network.

7) Sum of actually achieved link capacity: This metric is based on the principal component capacity or data rate. It calculates the sum of actually achievable link capacity in a WMN by considering the congestion over all links. This metric indicates the global impact of a certain channel assignment. One approach [20] uses this metric with the help of the Physical Interference Model.

8) Maximum channel load: This metric is also based on the principal component data rate. It calculates the total traffic load for all available channels in a WMN and then finds the maximum among them. This metric indicates the global impact of a certain channel assignment. A few approaches [12], [24] use this metric to balance traffic loads over all available channels.

9) Maximum unassigned traffic load of a link: This metric is also based on the principal component data rate. It calculates the traffic loads of all links that are not assigned to any channel and then finds the maximum among them. This metric indicates the global impact of a certain channel assignment. One approach [24] uses this metric to ensure fairness to all links in a WMN.

10) Channel cost: This metric calculates the cost of an available channel on the basis of its utilization, channel quality, I-factor [48], etc. This metric indicates the local impact of a certain channel assignment. One approach [25] uses this metric in two forms. In the first form, it calculates the cost using the weighted sum of utilization and quality of the channel. This value is used to assign a common channel. In the second form, it calculates the cost by multiplying three values - I-factor [48], channel usage, and queue length. This value is used to assign channels other than the common channels.

These metrics consider different issues and thus exhibit different impacts on the network. Among the metrics, maximum channel load and maximum unassigned traffic load of a link completely ignore interference. On the other hand, the sum of the actually achieved link capacity in the network can achieve the channel assignment with the lowest interference among all metrics. Therefore, it can also achieve the best transmission delay. However, it considers neither queuing delay nor switching delay. The sum of end-to-end throughput of all flows addresses these two issues and thus can achieve the best throughput in the network. However, neither of the metrics considers client mobility. Therefore, it remains an open area for future research.

Irrespective of the utilized metrics, the channel assignment algorithms follow a variety of operations during their assignment tasks. It is difficult to separately recognize and understand all of them. Categorization of the techniques can greatly facilitate understanding them from a high level within a short period of time. Therefore, next, we categorize the techniques.

V. Categorization of Channel Assignment Techniques

Channel assignment techniques exhibit significant diversity in their operations. Addressing the diversity from a macroscopic level, we can group the techniques into some categories. The categorization has a number of basis due to the presence of variation in underlying approaches of the techniques. Therefore, we adopt flat categorization on each basis rather than hierarchical categorization on all bases [34]. Fig. 5 presents the flat categorization. In addition to this categorization, some channel re-assignment techniques have been proposed in recent time [121], [122], [123], [128], which aim to re-configure the channels on a subset of radios to
All channel assignment techniques in WMNs can be classified into two categories based on the point of channel assignment decision - centralized and distributed.

1) Centralized Techniques: Centralized techniques take decisions from only one point - the center of the network. These techniques are practical in a managed WMN, which already contains a central entity. The central entity makes decisions about channel assignments to all links and then disseminates the information to all nodes in the network. The central entity must be aware of network topology along with other required information such as traffic load on each link, capacities of all available channels, etc., to perform the overall channel assignment. Many channel assignment techniques in the literature [2], [4], [5], [6], [8], [9], [11], [13], [14], [15], [16], [17], [18], [21], [23], [24], [27], [28], [30], [105], [108], [129], [131] adopt this approach.

The main advantage of these techniques is that they are amenable to a high degree of optimization as all required information is available at the central entity and the central entity exclusively makes decisions in the network. They also exhibit the ease in their upgradation as only one point is needed to be upgraded. Additionally, only one point of decision also enables the use of thin clients requiring no decision making at the clients. Such usage of thin clients permits to avoid any MAC modification that would be very troublesome and may lead to interoperability problems. Moreover, it is easier to maintain connectivity in centralized techniques as the network topology with information about all available channels is available to the central entity. However, network performance solely depends on the central entity in these techniques. Besides, these techniques suffer from a well-known problem called single point of failure, i.e., degradation in performance of only the central entity degrades the performance all over the network. In addition, for dynamic channel assignments, all nodes in the network have to inform the central entity about their current status and the central entity has to inform all nodes about their currently assigned channels on a regular basis. This requirement results in heavy control message overhead throughout the network. Furthermore, it is difficult for the central entity to capture some information about distant nodes such as environmental effects, external interference, client mobility, etc. Moreover, most of the WMNs do not have any central entity [47]. Therefore, a centralized technique is not applicable for most of the WMNs.

2) Distributed Techniques: Distributed techniques take decisions from all nodes in the network. These techniques are practical in both backbone WMN [47] and client WMN [47]. In these techniques, nodes can independently assign channels to their links based on their own and the other nodes’ information such as interference, traffic load, the number of available interfaces, etc. Nodes utilize this information through some metrics, which are already discussed in Section IV. Many channel assignment techniques [1], [3], [7], [9], [10], [11], [12], [19], [20], [25], [26], [29], [31], [32], [93], [94], [95], [131], [134] adopt the distributed approach.

In the distributed approaches, each node can utilize all of its locally available information such as environmental effect, external interference, client mobility, etc. Besides, for dynamic channel assignments, all nodes in the network have to inform their neighbors about their current status. This requirement results in a lower control message overhead than that in the centralized approach. Moreover, unlike the centralized approaches, the network performance does not depend on only one entity. Therefore, degradation in the performance of one node does not result in degradation in performance all over the network. However, it is difficult to maintain connectivity in distributed techniques as nodes often assign channels based on only the local information that does not ensure connectivity to all other nodes. Additionally, these techniques are not amenable to a high degree of optimization as all nodes in the network independently make their decisions. In addition, decision making at clients sometimes requires MAC modification, which is very cumbersome and may lead to interoperability problems. Moreover, these techniques force the responsibility of channel assignments on all the mesh nodes, which may result in difficulty in its upgradation.

B. Basis 2: Dynamicity

Channel assignment techniques can be classified into four groups based on their dynamicity - static, quasi-static, semi-dynamic, and dynamic.

1) Static Techniques: Static techniques assign channels to links at the beginning of deployment and keep the assignment unchanged throughout the lifetime of the network or for an extended period of time. These techniques are practical if the characteristics of WMNs are known in advance and the characteristics of WMNs are guaranteed to remain unaltered throughout the lifetime or the extended period. Most of the channel assignment techniques [2], [5], [6], [11], [12], [13], [14], [15], [16], [17], [18], [21], [23], [24], [26], [27], [28], [30], [32], [114], [133] in the literature are static in nature.
The main advantage of these techniques is that they can lead to a high degree of optimization as they can consider all prior information about a WMN during the channel assignment. Besides, one-time channel assignment guarantees avoiding channel switching delay. Moreover, there will be no control message overhead that is required to determine changes in WMNs. However, most of the WMNs cannot guarantee retaining their characteristics unaltered during their operation. Therefore, these techniques are not suitable for most of the WMNs. Additionally, these techniques assume two links as interfering if they are in interference range of each other even though both of the links may not always transmit data simultaneously in real time. Therefore, the assumption may lead to far from the optimal assignments considering the actual scenario of the network. In addition, these techniques cannot accommodate dynamic changes in environmental effects such as fading, bit error rate, etc. Therefore, they suffer from poor throughput in the case of any environmental change. Furthermore, these techniques cannot capture external interference and client mobility due to their inherently static nature. Finally, fixed channel assignments of these techniques might fail in the case of any unexpected disruption in WMNs as they cannot exhibit dynamic fault tolerance.

2) Quasi-Static Techniques: The second group, i.e., the quasi-static techniques, introduce a minimum dynamicity to the static techniques by assigning channels to links at the beginning of deployment and keeping the assignment unchanged until there arises any significant change in the characteristics of WMNs. These techniques are practical if the characteristics of WMNs are known in advance and the characteristics of WMNs are guaranteed not to change significantly in most of the time during their operations. A few channel assignment techniques [8], [9], [98] in the literature are quasi-static in nature.

These techniques can also lead to a high degree of optimization similar to the static techniques due to the consideration of all prior characteristics of WMNs during the channel assignment. Besides, they also adopt significant changes in WMNs. In addition, the strategy of keeping channel assignments fixed until occurring any major change in the network guarantees the optimization of channel switching at the interfaces that remain mostly stable during the operation of WMNs. Consequently, there will be little delay overhead due to the channel switching. Finally, there will be low control message overhead, required only to determine drastic changes in WMNs. On the other hand, if a WMN changes its characteristics frequently but not in significant manner, then quasi static techniques continue their operations with initial channel assignments that may gradually become far from the optimal one. Moreover, it is difficult to define what the significant changes in characteristics of WMNs are. In addition, these techniques are not suitable for WMNs with the mobile clients, as these clients may change their positions very frequently and hence require more dynamicity.

3) Semi-Dynamic Techniques: The semi-dynamic techniques increase the dynamicity of quasi-static techniques by periodically assigning channels to links of WMNs. The lifetime of a WMN is divided into some discrete disjoint intervals and these techniques assign channels at the beginning of each interval. These techniques are practical for most of the WMNs as there is no requirement to know the characteristics of WMNs in advance and those characteristics remain unaltered for a significant period of time similar to the quasi-static technique. Some channel assignment techniques [4], [9], [19], [20], [24], [25], [29], [31], [32], [102], [131] in the literature are semi-dynamic in nature.

The main advantage of these techniques is that they can accommodate the changing characteristics of WMNs. They can also adopt different dynamic changes such as environmental effects, external interference, and client mobility. Therefore, they can ensure high network throughput in dynamically changing WMNs. However, these techniques require periodic updates from all nodes in WMNs to accommodate and adopt the changes. These updates incur high control message overhead.

4) Dynamic Techniques: The dynamic techniques impose complete dynamic behavior by assigning channels to links of WMNs on the fly. These techniques assign channels whenever they are required to be assigned and monitor the appropriateness of the assignment continuously. These techniques are applicable to many types of WMNs as they do not require any prior knowledge for channel assignment. Few channel assignment techniques [1], [3], [7], [10], [26], [97] in the literature are dynamic in nature.

These techniques can provide the best accommodation for any change in characteristics of WMNs. Moreover, they can perfectly adopt different dynamic changes. Therefore, they can ensure high network throughput in dynamically changing WMNs. However, these techniques require continuous monitoring of surroundings to achieve complete dynamicity, which incurs continuous resource overhead. Moreover, these techniques require updates from all corresponding nodes in the case of any necessity to change an already established channel assignment and thus may incur high control message overhead. In addition, these techniques may frequently change channels in an unstable environment, which would result in high channel switching delay.

C. Basis 3: Granularity

Granularity of a channel assignment implies the minimum physical or logical entity to which channels are assigned. At the finest granularity, channels may be assigned on the basis of per-packet. This assignment is applicable to each individual packet. However, transmissions of different packets on different channels require frequent changes of channels, which result in the highest channel switching delay. Therefore, channel assignment at such a fine granularity is not practical, which can also be found from some recent studies [49], [50], [51]. As a result, channels are mainly assigned in three granularities in multi-radio WMNs - link-based, flow-based, and group-based.

1) Link-based Techniques: Link-based techniques transmit all packets over a wireless link between two nodes on the same channel until the channel assignment decision expires. Each link in a flow can choose any free channel for transmission. Most of the channel assignment techniques [1], [2], [4], [5],
four approaches to construct a group in the literature -

A few channel assignment techniques [28], [30] for multi-radio WMNs follow this approach.

These techniques can assign channels to links based on the surrounding conditions such as interference, environmental effects, etc., of that link. Moreover, independent channel assignment for a link can be done very quickly. Therefore, we can swiftly recover from any disruption in WMNs using these techniques. However, these techniques may use a number of channels for a single flow and the multiple channel usage along a flow may incur a significant channel switching delay. In addition, these techniques may trap to a local minima if they assign channels based on only the local information of a link.

2) Flow-based Techniques: At the second granularity, i.e., in the flow-based techniques, all packets of a single data flow between a source and a destination are transmitted on the same channel until the channel assignment decision expires. In other words, all links on a flow are assigned with the same channel.

A segment is defined in terms of a component. A component is defined as the largest set of connected nodes such that there exists a path from any node in the set to all other nodes in that set. A segment is defined as the largest subset of a component in which all nodes have access to at least one common channel that can be used to communicate among them.

For example, in Fig. 6, all nodes are equipped with two radio interfaces with two available channels. Due to the availability of connectivity between each pair, all nodes (A, B, C, D, and E) form a component. However, there are two segments due to the presence of two base stations. Channel 2 is available to the first segment consisting A, B, and C, whereas Channel 1 is available to the second segment consisting D and E. In [3], a segment-based approach is followed to decrease channel switching delay. This approach mainly addresses cognitive radio ad-hoc networks. Nevertheless, this approach may also be applied in WMNs due to the minimization of channel switching delay.

Group-based techniques can optimize different objective functions such as interference, connectivity, load balancing, etc., to a great extent. Besides, if we can assign the same channel to all links in a group, then we have to transmit packets only on that channel for flooding or multicasting in that group. Therefore, the cost of flooding and multicasting is minimized in a group-based approach. Moreover, if a group of links can operate on the same channel for a significant time period, then the channel switching cost will be minimized. However, these techniques cannot work only with local information as they require information about all nodes or links in the same group. Therefore, they result in significant control message overhead. In addition, these techniques slowly recover from any disruption in WMNs as the change in a channel assignment over a group requires the consideration of all links in that group.

D. Basis 4: Underlying Method

Channel assignment techniques for multi-radio WMNs use varying underlying methods in their operations. We broadly
classify these underlying methods into five categories - graph-based, optimization based, artificial intelligence based, peer-oriented, and others.

1) Graph-based Techniques: All graph-based approaches model a multi-radio WMN as a graph consisting of a set of vertices and a set of edges. Then, the channel assignment problem reduces the problem of assigning channels either to the set of vertices or to the set of edges. These approaches exploit four types of graph theoretic models - unit disk graph, connectivity graph, conflict graph, and multi-radio conflict graph. Fig. 7 depicts all these models.

A unit disk graph [52] is the intersection graph of unit circles. A vertex for each circle is taken, and two vertices are connected by an edge whenever the corresponding unit radius circles cross over each other. This model can be represented by an undirected graph, \( G = (V, E) \), where \( V \) is the set of vertices and \( E \) is the set of edges. To model a WMN as a unit disk graph, each node is mapped to a vertex and each pair of nodes within the transmission range of each other is mapped to an edge. Fig. 7a depicts a unit disk graph representation of a simple WMN, which has four nodes \( A, B, C, \) and \( D \). \( A \) and \( D \) can operate on both channels. Each node in the four pairs - \( (A, B), (B, C), (C, D), \) and \( (D, A) \) is in transmission range of each other. These are presented by four edges in the graph.

The second model, i.e., the connectivity graph [17], [21] of a network, is an undirected graph in which each vertex denotes a mesh node and an edge between two vertices denotes the existence of a transmission link between the corresponding nodes. Some research studies refer to this graph in varying ways such as a topology [27], [130], a network topology [4], [34], a communication graph [9], and a potential communication graph [6]. Fig. 7b shows a connectivity graph representation of the unit disk graph in Fig. 7a. There is a subtle difference between unit disk graph and connectivity graph. In a unit disk graph, an edge between two vertices implies the physical existence of corresponding nodes within the transmission range of each other. However, there may or may not be any active communication link between them. On the other hand, in a connectivity graph, an edge between two vertices implies the existence of an active transmission link between corresponding nodes.

The third model, i.e., the conflict graph [9], [17], [21], [107], [109], [133], is another undirected graph used to represent the potential interferences among the mesh nodes. Each edge in the connectivity graph is mapped to a vertex in a conflict graph. We put an edge between the two vertices in a conflict graph if and only if two links corresponding to the vertices are in interference range of each other. Interference can be modeled following either the Protocol Interference Model or the Physical Interference Model [110]. Some research refers to this graph as link interference graph [6] and interference graph [14], [15], [96]. Fig. 7c depicts the conflict graph corresponding to the connectivity graph in Fig 7b. Two edges in the conflict graph indicate that \( (A, D) \) edge in the connectivity graph is within the interference ranges of both \( (A, B) \) and \( (C, D) \) edges in the connectivity graph. However, \( (A, B) \) and \( (C, D) \) edges in the connectivity graph are not within interference range of each other. Therefore, there is no edge between the corresponding nodes in the conflict graph.

The fourth model, i.e., the multi-radio conflict graph [4], is also an undirected graph used to represent the potential interferences present among the radios in a WMN. Here, each vertex represents a pair of radios that are within transmission range of each other and each edge represents potential interference between two end vertices, i.e., the corresponding two pairs of radios. The multi-radio conflict graph is more complicated than the conflict graph, as the multi-radio conflict graph takes one vertex for each radio pair, whereas the conflict graph takes one vertex for each node pair. Fig. 7d depicts the multi-radio conflict graph corresponding to the connectivity graph in Fig. 7b. Here, channel number is shown as the suffix of node id.

All graph-based channel assignment techniques utilize one or more of the above mentioned models. Irrespective of the model, the techniques operate in one of three basic methods - graph coloring, graph partitioning, and breadth first search.

The graph coloring technique colors the elements of a graph under certain constraints such as no two adjacent elements get the same color. If we consider vertices as the elements to be colored, then the technique is called vertex coloring, and if we consider edges as the elements to be colored then the problem is called edge coloring. Graph coloring-based channel assignment techniques consider channels as colors. The number of channels is generally limited in a WMN. Therefore, the graph coloring method has to maintain the constraint on the number of available channels. Besides, this method provides some form of approximation to obtain a solution for channel assignment in a WMN. Some channel assignment techniques [2], [9], [17], [111] use graph coloring with different approximation methods. Examples of such ap-
proximation methods are sub-graph coloring [2], local search [9], and greedy method [17], [27].

The second basic method, i.e., graph partitioning, generally divides a graph into sub-graphs such that the size of the generated sub-graphs is almost the same and connections among the sub-graphs are minimized. In a channel assignment, vertices of a conflict graph are partitioned into some interference sets or collision domains using some heuristics [6] or approximations such as the greedy method [14], [15] as the graph partitioning problem is known to be NP-complete.

The third basic method, i.e., breadth first search (BFS) [59], is a search algorithm that starts at the root node and explores all the neighboring nodes of the root node in a graph. Then, it explores the unexplored neighbor nodes of each of the neighboring nodes of the root and so on. Some channel assignment techniques [4], [5], [16], [18] assign channels to vertices of a conflict graph following the BFS.

The main advantage of a graph-based technique is that it can achieve high optimization as it assigns channels based on the complete network topology. Besides, these techniques can easily maintain connectivity as the network topology is available during the channel assignment. Moreover, polynomial time algorithms of graph-based techniques can exhibit low time complexity. However, these techniques require the complete network topology during the channel assignment. Therefore, dynamic graph-based techniques [4], [9], [14], [15] incur control message overhead. In addition, it is difficult to maintain a stable network topology if the network contains any mobile client that frequently changes its position.

2) Optimization-based Techniques: The second category based on the underlying methods, i.e., optimization-based techniques, models a channel assignment problem as a set of equations. Then, the approach optimizes some objective functions using the equations. These approaches generally exploit three types of formulation - Integer Linear Programming, Semidefinite Programming, and Superimposed codes. Nonetheless, a few approaches in the literature [102], [103], [143] exploit the notion of game theory while performing channel assignment.

A linear programming [60] method is defined as an approach to finding the values of some unknown variables that maximizes or minimizes a linear function subject to one or more linear constraints. If the values of the unknown variables are restricted to be integers, then the problem is called an integer linear programming (ILP) problem. In a channel assignment problem, we have a number of constraints such as a limited number of interfaces on a node, a limited number of available channels, a limited capacity of each available channel, etc. Moreover, the solution of the problem decides whether we should activate or deactivate a channel on a link. Therefore, we can assume the activation as 1 and the deactivation as 0 with the constraints and formulate the channel assignment problem as an ILP problem. Some research studies [6], [11], [12], [13], [36], [91], [92], [106] solve the channel assignment problem using ILP.

The second type of optimization-based techniques, i.e., semidefinite programming [61], optimizes a linear objective function subject to a constraint, which is a combination of symmetric matrices in an affine space. The constraint is nonlinear, non-smooth, and convex. Therefore, semidefinite programming problems are convex optimization problems. Semidefinite programming unifies several standard problems such as linear and quadratic programming. Semidefinite programs are more general than linear programs, although having the similar complexity to solve a problem. Few channel assignment techniques [9], [16] map the channel assignment problems to semidefinite programming problems. Their formulations are similar to the formulations of semidefinite problems for Max K-cut [62] and Vertex Coloring [63].

A binary superimposed code [67] consists of a set of code words whose digit by digit boolean sum (1 + 1 = 1) possesses a distinguishable prescribed level. One possible option for the prescribed level is to imply that no code word in the set is a bitwise OR of a subset containing some other codes in the set. More formally, a $N \times t$ binary matrix is called a superimposed code of length $N$, size $t$, strength $s$, and maximum list size $L - 1$, if the boolean sum of any subset of $s$ code words in the matrix covers a maximum of $L - 1$ code words that are not components of that subset. This code is called $(s, L, N)$-code of size $t$. The binary matrix can be called an $s$-disjunct code if and only if the boolean sum of any subset of $s$ code words in that matrix does not cover any code word that is not in the subset. More precisely, we get $L = 1$ for a disjunct code and thus a superimposed $(s, 1, N)$-code is a $s$-disjunct code. The concept of $s$-disjunct code is utilized by a channel assignment technique [26] that considers a code word for each mesh node. Here, each channel corresponds to a row and each node corresponds to a column in the matrix.

The important advantage of optimization-based techniques is that they can highly optimize the channel assignment by reaching the global optima by solving a set of equations. Moreover, these algorithms have a very low time complexity and a fast convergence rate. However, it is difficult to efficiently calculate an objective function in the presence of varying phenomena. Examples include the presence of a mobile client, which frequently changes its position. Therefore, optimization-based techniques cannot be efficiently adapted for mobile clients.

3) Artificial Intelligence based Techniques: Artificial intelligence (AI) [64] enables a system to perceive its environment before making decisions to maximize its extent of success. Some techniques of channel assignment use AI-based approaches to make probabilistic decisions to optimize their objective functions. There are two AI methods that are generally utilized by the channel assignment techniques - Genetic Algorithm and Tabu search. Another AI-based method, Q-learning [1], is proposed for channel assignment in wireless sensor networks to reduce interference, and this approach can also be implemented in a WMN to minimize interference.

Genetic algorithm (GA) [65] is a stochastic global search technique that starts with an initial decision and then optimizes the decision in a search space. Genetic algorithm is a particular type of Evolutionary Algorithm (EA) that uses several steps such as selection, mating, crossover, and mutation, which are inspired by evolutionary biology. Selection, mating, and crossover guarantee inheritance, whereas mutation facilitates
nodes in a WMN make their decisions locally and completely. This approach incurs high control message overhead in a WMN. Besides, all these approaches, and such information collection process may trap a local optima. Therefore, the iterations of these evolutionary steps guide to exact or approximate global optima in a search space. In a channel assignment technique, GA starts with a set of initial channel assignments and then improves them over a number of consecutive iterations of the evolutionary steps. Few channel assignment techniques [8], [11], [46] use GA to achieve the optimal decision. Another type of EA named Particle Swarm Optimization (PSO) is also used [125], [127] to design channel assignment techniques in WMN.

Tabu search [66] is a meta-heuristic-based stochastic optimization method. It leads to a local heuristic search procedure that explores the decision space beyond a local optimality. Tabu search enhances the performance of a search method by using adaptive memory structures, which enables marking all previously determined potential decisions so that it does not visit those possibilities again. Moreover, the adaptive memory enables the search method to reconcile with previously determined potential decisions to effectively exploit them. Few channel assignment techniques [9], [21], [22] utilize Tabu search while optimizing their decisions.

AI-based techniques ensure fast convergence and good approximation of the global optima by incorporating stochastic nature to their search methods. They can create a knowledge base that helps to quickly provide good channel assignments under dynamic changes in a WMN. However, the extent of optimization of the channel assignments depends on the number of iterations used in the AI-based techniques. Therefore, the performances of these techniques are limited by the number of iterations. Besides, the storage requirement of all possible channel assignment decisions may incur high space complexity.

4) Peer-oriented Techniques: Peer-oriented approaches operate on each mesh node based on the information collected from peer nodes. A number of channel assignment techniques [7], [9], [10], [11], [20], [19], [29], [31] follow such peer-oriented approaches. However, they significantly vary over their methods of collecting information from the peer nodes. They can use broadcasting [19], [20], [29] or three-way handshaking [10], [11] or multicasting [31] or a combination of broadcasting and unicasting [7], [9] or even a combination of overhearing, multicasting, and broadcasting [32].

The most important advantage of the peer-oriented approaches is that they do not make any assumptions about network topology or traffic load. Therefore, these approaches can easily adopt dynamic characteristics of a WMN. Moreover, all of these approaches are inherently distributed in nature. Therefore, they do not require any central entity in the network, and thus degradation of performance of one node does not result in the degradation of performance all over the network. Moreover, each node can utilize all of its locally available information such as environmental effect, external interference, client mobility, etc. However, each node in the network collects information from all of its peer nodes in these approaches, and such information collection process incurs high control message overhead in a WMN. Besides, all nodes in a WMN make their decisions locally and completely independently. Therefore, the overall decision of the network may trap a local optima. In addition, a mesh node cannot solely select the neighbor nodes that must be connected to maintain a complete network connectivity by only using the information collected from the peer nodes. Therefore, it is difficult to maintain connectivity in these approaches.

5) Other Techniques: There are some other techniques [3], [23], [24], [25], [28], [30], [100], [101], [116], [124], [142], [145], [147] that do not follow any of the previously mentioned approaches. They execute their own greedy methods in one or more phases to optimize their objective functions. We point out this sort of greedy approaches, such as Load-Aware Channel Assignment/ Routing [28], RCL [30], MCCCA [23], BSCA and PDCA [24], CoMTaC [25], and Segment-Based Channel Assignment [3] in Section III.

These approaches can optimize their objective functions to a great extent using different greedy methods. Moreover, some of these approaches [28], [30] exploit cross-layer advantages such as usage of routing or scheduling information to optimize their channel assignment decisions. However, these approaches are completely application specific. In addition, these approaches have to take some extra measures to ensure network connectivity. For example, CoMTaC maintains a spanner graph of the network topology to ensure connectivity. Therefore, it is difficult to maintain connectivity using these approaches. We further discuss on these approaches in the following subsection.

E. Basis 5: Spanning Layers in OSI

Most of the channel assignment techniques operate in Layer 2, i.e., Data Link Layer. However, some of the approaches also involve other layers of OSI model [135] in their operations. Consequently, we can classify channel assignment techniques in WMNs into two categories based on their operation spanning layers in OSI - single-layer and cross-layer.

1) Single-Layer Techniques: These techniques utilize only the information available at the Data Link Layer while assigning channels to different network interfaces. Most of the channel assignment techniques in the literature [2], [4], [5], [6], [8], [9], [10], [11], [13], [16], [18], [19], [23], [26], [94], [98], [102], [109], [129], [130], [131], [132] follow this approach.

The advantage of utilizing such approach is that it does not demand cross-layer information, and thus can retain classical layered architecture while operating in a network. However, the other side of the coin is that the techniques following this approach may not achieve high network performance due to not utilizing the cross-layer information.

2) Cross-Layer Techniques: Cross-layer channel assignment techniques involve upper layers of OSI model in addition to Data Link Layer in their operations. Examples include involving Network Layer (i.e., Layer 3) for joint channel assignment and routing [27], [28], [29], [30], [32], [91], [101], [116], [134], [141], [142], [144] and involving Transport Layer (i.e., Layer 4) for channel assignment with congestion control [113], [123], [137]. These techniques exploit cross-layer information such as routing path from Network Layer and traffic allocation from Transport Layer while assigning channels to
different network interfaces to optimize the performance of their assignments.

The obvious advantage of utilizing such approach is that the techniques following this approach can achieve significantly-improved network performance due to utilizing cross-layer information. However, the utilization of the cross-layer information breaches the classical layered architecture, and thus may become difficult to implement in networks that are already in operation.

The above categorization provides a high-level view over the channel assignment techniques in the literature. Next, we present an exhaustive comparison among the state-of-the-art channel assignment techniques, which we discussed in Section III.

VI. COMPARISON AMONG DIFFERENT CHANNEL ASSIGNMENT TECHNIQUES

In this section, we thoroughly compare different aspects of the already described channel assignment techniques. The design issues illustrated in Section II are the bases of our comparison. We classify the issues into two categories - primary and secondary. Primary issues are very crucial to ensure efficiency and effectiveness of a channel assignment technique in most of the applications. We identify interference, end-to-end delay, connectivity, throughput, stability, and scalability as the primary issues. On the other hand, secondary issues are mainly supplementary to increase efficiency and effectiveness of a channel assignment technique. We consider all the issues other than primary ones as secondary issues.

Note that our evaluation of channel assignment techniques is based on their consideration of the different design issues. The evaluation does not imply any outcome of unified experimental results. The diversity in the modes of operation and underlying approaches adopted in the techniques, as presented through Fig. 5 render unified evaluation a cumbersome work to do, which might also become near-to-impossible due to the diversity. A few studies in the literature have attempted to perform such evaluation, however, for some specific types of techniques. For example, only graph-based techniques are evaluated through MATLAB simulation in [133] and only centralized techniques are evaluated through ns-2 simulation in [130]. On the other hand, our evaluation focuses on comparing all the techniques based on their comprehensiveness in considering the different design issues.

We present our comparison in two steps. We use the notion presented in Table I in both steps. The symbols indicate whether or not, a particular design issue is considered by a channel assignment technique. Here, if a particular design issue is considered by a channel assignment technique, we put a check mark (√) on that corresponding table entry. Otherwise, we put a cross mark (×). Besides, we use a double check mark (√✓) to denote primary or strong consideration of a design issue. For example, CLICA [17] ensures network connectivity and stability while assigning channels. Therefore, these two design issues are primarily considered by this technique and we put double check marks in their table entries. On the other hand, as CLICA completely ignores external interference, queuing delay, and switching delay, we put cross marks in their table entries. Finally, we use a single check mark for the other design issues that are considered, however, not guaranteed by CLICA. For instance, CLICA does not guarantee minimizing interference or maximizing network throughput. However, while assigning channels, CLICA tries to minimize interference by ensuring network connectivity, which eventually facilitates achieving high throughput in the network. Consequently, we put a single check mark in table entries for interference (intra-flow and inter-flow) and throughput.

Following this process of evaluation, we compare the techniques based on the primary issues in the first step (Table II), and then based on the secondary issues in the second step (Table III). These comparisons can help us in choosing the appropriate techniques in different applications. For example, Probabilistic Channel Usage based channel assignment [29] should best serve simple applications demanding low-cost deployment. On the other hand, we should adopt CoMTaC [25], Hyacinth [31], or Two-hop clustering based channel assignment [32] in case of applications requiring high-throughput and scalability. These techniques also perform well for applications demanding low delay due to having stringent constraint on end-to-end delay. In addition, we can also exploit MRBFS-CA [4] and RCL [30] for such applications demanding low delay. Now, to better present applicabilities of the channel assignment techniques in real applications, we briefly describe choices among different techniques for some specific prominent applications in the next section.

VII. REAL LIFE ASPECTS OF DIFFERENT CHANNEL ASSIGNMENT TECHNIQUES

The recent developments of multi-radio WMNs have introduced several real deployments and various applications [47]. In this section, we discuss a number of such real deployments and various promising applications of multi-radio WMNs, along with the applicabilities of different channel assignment techniques in these cases.

A. Real Deployments

There exists a number of experimental real deployments of multi-radio WMNs which provide a good ground for implementation and evaluation of various new protocols and channel assignment techniques. Here, we discuss several well studied real deployments both in industry and research area.

1) MIT Roofnet Mesh Network: The Roofnet [154], [155], developed at MIT, is an experimental multi-hop 802.11b/g mesh network intend to provide broadband Internet access to users in Cambridge. It consists of a number of mesh nodes spreading over a few square kilometres of the city. Each node consists of a desktop computer running a special
TABLE II: Comparison of channel assignment techniques based on primary issues

<table>
<thead>
<tr>
<th>Technique</th>
<th>Interference</th>
<th>Channel</th>
<th>Transmission</th>
<th>Queuing</th>
<th>Switching</th>
<th>Connectivity</th>
<th>Throughput</th>
<th>Stability</th>
<th>Scalability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intra flow</td>
<td>Delay</td>
<td>Diversity</td>
<td>delay</td>
<td>delay</td>
<td>delay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLICA [17]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MRBFS-CA [4]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TARICA [18]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TICA [111]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ISDP [16]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Superimposed code [26]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>NSGA-II [8]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DPSO-CA [125]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>GTS [21]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Q-Learning [1]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ADCA [69]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Probabilistic Channel Usage [29]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hyacinth [31]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SAFE [19]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>JOCAC [20]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Two-hop clustering [32]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CoMTaC [25]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Neighbor Partitioning [28]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Load-Aware [28]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>RCL [30]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MCCA [23]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>JSICA [24]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PDCA [24]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

TABLE III: Comparison of channel assignment techniques based on secondary issues

<table>
<thead>
<tr>
<th>Technique</th>
<th>Locality of Information</th>
<th>Distributivity</th>
<th>Dynamicity</th>
<th>Fairness</th>
<th>Load balancing</th>
<th>Fault tolerance</th>
<th>Client Mobility</th>
<th>Common channel rate</th>
<th>Convergence Ctrl msg. overhead</th>
<th>Synch.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLICA [17]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MRBFS-CA [4]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TARICA [18]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TICA [111]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ISDP [16]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Superimposed code [26]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>NSGA-II [8]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DPSO-CA [125]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>GTS [21]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Q-Learning [1]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ADCA [69]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Probabilistic Channel Usage [29]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hyacinth [31]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SAFE [19]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>JOCAC [20]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Two-hop clustering [32]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CoMTaC [25]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Neighbor Partitioning [28]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Load-Aware [28]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>RCL [30]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MCCA [23]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>JSICA [24]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PDCA [24]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

pre-installed Roofnet software, an 802.11b/g radio, and an omni-directional roof mounted antenna. Roofnet was initially designed for providing Internet access as a community network. The architecture and operation of Roofnet requires considering load balancing, scalability, and distributivity in order to enhance overall performance. Therefore, channel assignment algorithms such as CoMTaC [25], Hyacinth [31], two-hop clustering based channel assignment [32], etc., are good choices for this deployment.

2) WING: The WING, Wireless Mesh Network for Next-Generation Internet project [156], is funded by Italian Ministry of University and Research and led by CREATE-NET and Technion. Part of this project is built on top of Roofnet by adding supports for multiple radio interfaces, WCETT routing metric, and autonomic channel assignment. Besides, it supports features such as adaptive traffic aggregation, opportunistic scheduling, QoS provisioning, etc. The existence of auto-configuration feature makes WING suitable for emergency and disaster systems. Channel assignment techniques such as Q-Learning [1], MRBFS-CA [4], CoMTaC [25], and RCL [30] are best suited for such architectures having auto-configuration and quick-propagation features.
3) SMesh: SMesh system [157] is developed by the Distributed System and Networks Lab at Johns Hopkins University. It provides peer-to-peer connectivity, Internet connectivity, and fast hand-off to mobile clients across the mesh. In SMesh system, clients get connected automatically sparing the necessity of installing any additional software or drivers on their devices. This system requires the consideration of seamless connectivity and client mobility for its operation. Therefore, channel assignment techniques ensuring these requirements, such as SAFE [19] and Probabilistic Channel Usage [29], are suited for this WMNs environment.

4) UCSB MeshNet: UCSB MeshNet [158] is an experimental real deployment developed on the campus of University of California, Santa Barbara. Each mesh node of UCSB MeshNet consists of two Linksys WRT54G wireless routers strapped together. UCSB MeshNet is mainly used to conduct experiments for developing scalable routing protocols, efficient network management, multi-media streaming, and QoS for multi-hop wireless networks. These applications mainly require to consider connectivity, stability, and distributivity to achieve reasonable network performance. Therefore, channel assignment techniques such as CoMTaC [25], Probabilistic Channel Usage [29], and Hyacinth [31] are best suited for UCSB MeshNet.

5) CUWiN: The Champaign-Urbana Community Wireless Project (CUWiN) [160] focuses to develop decentralized, community-owned, and non-profit mesh networks. This project is sponsored by the Urbana-Champaign Independent Media Center. The main focus of CUWiN is to provide community-owned services, which implies that its channel assignment technique must consider design issues such as scalability, stability, high throughput, etc. Therefore, channel assignment algorithms such as CoMTaC [25], Hyacinth [31], two-hop clustering based channel assignment [32], and ADCA [69] are good options in this case.

6) Mpumalanga Mesh: Mpumalanga Mesh [161] project aims to connect local people of Mpumalanga Province to the Internet, local information repositories, and voice resources at clinics, farms, homes, and schools through low-cost wireless connectivity. Channel assignment techniques satisfying the requirements of such facility systems, for example, stable connectivity, fairness, and better throughput, can be suitable for the project. Therefore, channel assignment techniques such as TARICA [18], Superimposed Code based [26] and Probabilistic Channel Usage [29] are suitable for this deployment.

7) Microsoft Mesh Connectivity Layer (MCL): Microsoft Research carries out a project [162] named Self Organizing Wireless Mesh Networks that focuses on developing community-based WMNs. The aim of this project is to allow neighbors to connect their home networks together. In this project, ad-hoc routing and link quality measurement is implemented in a module named Mesh Connectivity Layer (MCL). MCL is being used mainly for investigating different routing and MAC layer protocols for multi-radio multi-channel WMNs. The environment of WMNs, driven by MCL, requires to consider connectivity, scalability, and distributivity during assignments of channels. Therefore, channel assignment techniques such as Q-Learning [1], SAFE [19], CoMTaC [25], Probabilistic Channel Usage based channel assignment [29], etc., can be used in this deployment.

8) Other Real Deployments: There exists several other real deployments of WMNs both in academic research and industry, such as iMesh [159], BelAir [163], Strix Systems [164], Tropos [165], Firetide [166], TAPs project [167], Quail Ridge wireless mesh network [168], etc. The architectural and operational characteristics of these deployments are more or less similar to the ones we have discussed above.

The desired characteristics determine which design issues we should consider while designing channel assignment techniques for the real-deployments, and hence, quantifies the applicability of the state-of-the-art channel assignment techniques.

B. Major Applications

Now, we discuss some promising applications of WMNs along with their requirements for channel assignment techniques.

1) Broadband Home Networking: A WMN provides a simple, manageable, and low-cost solution for broadband home networking. Connectivity, stability, throughput, and fairness are the most important design issues for designing channel assignment techniques for this application. On the other hand, this application does not require to consider scalability, load balancing, and client mobility. Therefore, channel assignment techniques such as MRBFS-CA [4], CoMTaC [25], RCL [30], TICA [111], etc. are good choices for this application.

2) Community, Enterprise, and Metropolitan Area Networking: Community networking connects several home networks. This is another major application of multi-radio WMNs that requires considering distributivity, scalability, and load balancing. Therefore, CoMTaC [25], Hyacinth [31], and Two-hop clustering based channel assignment [32] are good options to be utilized in this application. On the other hand, enterprise networking resembles a small network within an office or a medium-size network connecting all offices in an entire building or a large scale network connecting offices in multiple buildings. It requires dynamicity to adopt dynamic arrivals of clients in addition to other requirements such as scalability, high throughput, and stable communication. Therefore, MRBFS-CA [4], CoMTaC [25], Probabilistic Channel Usage based channel assignment [29], Hyacinth [31], and Two-hop clustering based channel assignment [32] and can be used for this application. Lastly, metropolitan area network connects a number of home networks, community and enterprise networks. The major requirement of this application is to maintain scalability due to operating with a large number of clients over a large area coverage along with stability, high throughput, distributivity and dynamicity. The same channel assignment techniques which are used in community and enterprise networking can also be used in case of metropolitan area networking.

3) Facility Systems: Multi-radio WMNs provide several promising applications in various facility systems such as health and medical systems, transportation systems, and educational systems. Since a health and medical system monitors and processes different diagnosis data in a hospital or
medical center, it does not impose any strict requirements on the network performance. On the other hand, transportation and educational systems require stable connectivity with the consideration of client mobility and distributivity. Therefore, Q-Learning [1], SAFE [19], and Probabilistic Channel Usage based channel assignment [29] are suitable choices for these applications.

4) Emergency and Disaster Networking: Multi-radio WMNs can provide stable connectivity to propagate emergency and disaster information such as flood forecast, earthquake alarm, wildfire locations, etc. This application requires quick propagation and thus imposes strict requirements on end-to-end delay and convergence rate. Therefore, channel assignment techniques such as NSGA-II [8], ISDP [16], JOCAC [20], GTS [21], and Superimposed code [26] based channel assignment are suitable for these applications.

5) Military: Thousands of microchip-size mesh nodes can be dropped onto a battlefield to set up instant scouting and surveillance networks. This application imposes strict requirements on dynamicity, fault tolerance, client mobility, scalability, and distributivity in addition to supporting guaranteed connectivity. It is extremely challenging and still an open research problem to design an efficient channel assignment algorithm which fulfills all the requirements. However, channel assignment techniques such as SAFE [19] and Probabilistic Channel Usage based channel assignment [29] can partially meet the requirements.

6) Other Applications: Multi-radio WMNs also provide simple and low cost solutions for building automation and security surveillance systems. A building automation system controls and monitors various electrical devices, whereas, a surveillance system captures and manipulates still images and videos over the network. Guaranteed connectivity along with high throughput is required for these systems. Therefore, MRBFS-CA [4], Load-aware [28], RCL [30], Hyacinth [31], CLICA [17], TARICA [18], MCCA [23], CoMTaC [25], and Two-hop clustering [32] are the prominent candidates to be utilized in this application.

Moreover, multi-radio WMNs are useful for peer-to-peer communication among devices such as laptops, PDAs, etc. This application requires dynamic and distributed connectivity support in the operational environment. Therefore, we can utilize SAFE [19] and Distributed Self-stabilizing channel assignment [10] to meet these requirements.

Most existing channel assignment techniques are designed for one or more type of applications which we discussed above. However, few applications exhibit diverse and challenging requirements that make the state-of-the-art techniques inapplicable. In addition, there are few other issues that still remain as open problem for future research. We focus on these areas in the next section.

VIII. GUIDELINES TO FUTURE RESEARCH

Many of the channel assignment techniques in the literature simplify their analysis by adopting simple models such as Protocol Model. Moreover, some issues are completely ignored by most of the techniques. Consequently, there are still several doors open for further research in this area. Next, we highlight some areas that may be addressed in the future research.

A. Dynamic Techniques with Physical Model

Most of the research studies adopt the Protocol Model to capture interference of the network. However, the Physical Model is more practical than the Protocol Model. Therefore, it is worth spending more effort to capture the interference using the Physical Model. A few techniques [5, 9, 20, 25] consider the Physical Model to achieve better performance. Nonetheless, none of them provides a dynamic technique. Dynamic techniques for channel assignment are of the utmost importance to cope with dynamic interference over unlicensed bands [138] and other network dynamics [139]. Such techniques can work best in accordance with Physical Model, as Protocol Model lacks the ability of properly accumulating the dynamics due to its simplified nature of operation. Therefore, a dynamic technique with the Physical Model remains an open area having utmost significance for future research.

B. External Interference

Multi-radio WMNs mainly operate over IEEE 802.11 and 802.16 standards. These standards use an unlicensed RF band. Therefore, these bands can also be used by some other devices not within the WMN. Usage of the bands by the devices, being outside of a WMN but within the interference regions of some mesh nodes, results external interference. Moreover, the increasing usage of different personal wireless devices such as PDAs, laptops, etc., poses a greater threat to interference-free operation of WMNs. Therefore, external interference should be considered with the utmost importance to guarantee high network throughput. Nevertheless, this phenomena is completely ignored by most of the channel assignment techniques in the literature.

MRBFS-CA [4] considers the external interference during its channel assignment. However, this technique requires a centralized server that may not be available in many applications of WMNs. Another channel assignment technique, CoMTaC [25] also considers external interference. Nonetheless, its consideration depends on only some randomly chosen nodes that monitor channel quality in the network. Moreover, neither MRBFS-CA nor CoMTaC provides dynamic solution. Therefore, more research effort should be devoted to efficiently capture the external interference during a channel assignment.

C. Switching Delay and Queuing Delay

Most of the channel assignment techniques for multi-radio WMNs ignore switching delay. Even though OSS [3] and Channel assignment for Multi-casting [7] provides significant minimization in switching delay, these two techniques are completely application specific - the first one is for opportunistic bandwidth sharing and the second one is for multi-casting. Probabilistic Channel Usage [29] is the only application independent technique that minimizes the switching delay. However, it only uses a threshold for time or number of message transmitted on a certain channel to improve the
switching delay, which may be far away from the optimal solution. On the other hand, queuing delay is also ignored by most of the channel assignment techniques. Even though CoMToC [25] improves the queuing delay by considering queue lengths, and Probabilistic Channel Usage [29] partially minimizes the queuing delay by imposing fairness among different queues, neither of them provides a complete dynamic approach with the minimization.

In addition, Probabilistic Channel Usage is the only technique that partially considers both queuing delay and switching delay with some constraints over them. However, simultaneous constraint-free considerations of both of them may significantly improve end-to-end delay in a WMN. Therefore, simultaneous improvement of queuing delay and switching delay can be addressed in future research.

D. Client Mobility

Client mobility obtains little emphasis in the channel assignment techniques in the literature, though some applications such as a transportation system and coverage of an educational institution are required to support this. Here, Q-Learning [1] can support the dynamic clients even though it is actually intended for wireless sensor networks. Probabilistic Channel Usage [29] and SAFE [19] also provide support to mobile clients. However, both of them require broadcasting for this purpose. Moreover, none of them propose any solution for the suitable hand-off of mobile clients. Therefore, more research is needed to efficiently support the mobile clients in multi-radio WMNs.

E. Fairness

Some techniques such as Probabilistic Channel Usage, TARICA [18], SAFE [19], PDCA [24], and Superimposed code-based channel assignment [26] impose fairness during their channel assignments. However, all of them except the Superimposed code-based technique increase interference in the network to achieve the fairness. On the other hand, the Superimposed code-based technique only provides fairness to static clients. However, different network services (spanning from file transfer to real-time multimedia) that are provided through WMNs having static and mobile nodes may need enhanced fairness [139] in accordance with interference minimization. Therefore, fairness with interference minimization in a WMN consisting of both static and mobile clients might be addressed in future research.

F. Quality of Service (QoS)

None of the channel assignment techniques in the literature considers QoS during the channel assignment even though the consideration of QoS plays a crucial in successful advancement of WMNs [139]. The assignment of channels in a WMN controls the link capacity reservation, which is a fundamental resource to ensure QoS. Therefore, extensive research is required on device channel assignment techniques to support QoS in multi-radio WMNs.

IX. Conclusion

The increasing popularity of wireless technology encourages researchers to explore new dimensions in wireless mesh networks. Multi-radio WMNs are one of the recent dimensions in this area. With the introduction of the multi-radio technologies, an obvious challenge emerges - channel assignment to the radio interfaces of a multi-radio mesh node. Extensive research has been conducted to efficiently perform such channel assignment.

In this paper, we make an effort to present state-of-the-art channel assignment techniques for multi-radio WMNs. Our elaboration provides a step-by-step illumination of the techniques. We start with brief descriptions of design issues that are related to the channel assignment. Subsequently, we briefly describe some important channel assignment techniques by grouping them based on their underlying methods. We also articulate their pros and cons. Then, we illustrate different channel assignment metrics used in the literature and also analyze their applicability. Then, we propose a taxonomy for already-proposed channel assignment techniques. Our taxonomy provides a detail categorization based on five aspects - point of decision, dynamicity, granularity, underlying method, and spanning layers in OSI. In addition, we compare them based on all design issues. Besides, we point out several real deployments and the applicabilities of the channel assignment techniques in pragmatic scenarios. Finally, we conclude our work by presenting some guidelines for future research in this area.

In spite of having a number of research studies in the literature, the ultimate maturity of the channel assignment techniques for multi-radio WMNs is yet to be achieved. Some issues such as client mobility, QoS, etc., are not efficiently considered in the already-available techniques till now. Therefore, more research effort is necessary to strengthen this area to secure the ultimate success of multi-radio WMNs.

REFERENCES


