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Review

Review of channel assignment approaches in multi-radio multi-channel wireless mesh network

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ABSTRACT

The Channel Assignment (CA) is an efficient tool to exploit multiple non-overlapping channels to minimize interference and enhance the capacity of the wireless mesh network. Even though the CA can minimize the total network interference, its result may cause some design issues which influence the network performance. First, the CA alters the network topology which in turn may produce unconnected logical topology. Second, the interaction between the CA and routing protocol where the effective capacity of each link depends on the routing decision and the result of CA. In this article we focus on multi-radio, multi-channel wireless mesh network. First, we defined the channel assignment (CA) design issues. Second, we classified the CA approaches based on the main design issues. For each CA approach, its advantages and limitations are highlighted. Third, the overall comparison for the classification is given in details. Finally, we discussed the future research direction for channel assignment.

Contents

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1. Introduction

Over the last few years, Wireless Mesh Network (WMN) has used by many wireless technologies as last-mile Internet access of application scenarios such as public safety networks, broadband Internet access, campus networks and mobile telephony networks (Akyildiz et al., 2005). The WMN is composed of mesh routers that collect and relay the traffic generated by mesh clients. Mesh routers are usually stationary and equipped with multiple radio interfaces. Mesh clients are typically mobile, and data are relayed by mesh routers to the intended destination. One or more mesh routers may have gateway functionality and provide connectivity to other networks such as Internet access.

In traditional wireless networks, each node is equipped with a single radio interface and operates on a single wireless channel. Due to interference and packet collision in the single shared medium, the network capacity of this single-interface, single-channel wireless network decreases as the number of wireless nodes increases (Chiu et al., 2009). The problem is more serious in the wireless mesh network, due to interference caused by adjacent nodes on the same path as well as from neighboring paths. It has been shown that only 1/7 of the channel capacity can be used in a chain topology (Chiu et al., 2009).

The Channel Assignment (CA) is an efficient tool to exploit multiple non-overlapping channels to minimize interference and enhance the capacity of the wireless mesh network. It tries to find a feasible mapping between wireless channels and radio interfaces at each node with the aim of minimizing the interference and improving the capacity of WMN network. The frequency of IEEE 802.11b/g and IEEE 802.11a is divided into 14 channels, within 3 non-overlapping channels, and 19 channels, within 11 non-overlapping channels, respectively (Raniwala et al., 2004; Raniwala and Chiueh, 2005). Even though the CA can minimize the total network interference, its result may cause three main issues which influence the network performance. Firstly, the CA alters the network topology which in turn may produce unconnected logical topology. Secondly, the interaction between the CA and routing protocol is another issue need to be addressed during the channel assignment stage. Some of CA approaches neglect the routing during the channel assignment. However, such approaches fail to consider the traffic load in their solution. In addition, their results may increase the path length, which in turn influences the packet end-to-end delay. Many objectives of channel assignment such as fairness, quality of services, throughput and traffic-aware depend on the node connectivity and routing decision. Therefore, joint the routing and network connectivity with channel assignment during the channel assignment design stage is one of the main factors that can efficiently optimize the multi-radio multi-channel resources. Finally, the stability of channel assignment which refers to how frequently the channel assignment is performed. The details of channel assignment issues are addressed in Section 2.

Many surveys of channel assignment have been proposed based on their own classification (Skalli et al., 2007; Si et al., 2010; Ding and Xiao, 2011; Islam et al., 2015). In Skalli et al. (2007), the channel assignment is reviewed based on static, dynamic and hybrid classification. In Si et al. (2010), the authors classified the channel assignment approaches according to the point of decision as centralized and distributed. In Ding and Xiao (2011), the channel assignment in both Omi-directional and directional antenna are covered. Besides these surveys, some works review the existing channel assignment based on joint channel assignment with routing (Qu et al., 2016) and topology control (Liu and Bai, 2012). Our paper differs from the previous works in three aspects.

- We develop a new taxonomy to classify the on-going channel assignment in multi-radio multi-channel WMN based on the main design issues of channel assignment. This taxonomy is built through identifying the characteristics of proposed channel assignment to address the design issue of channel assignment.
- We review link optimization approaches, minimizing the total number of logical topology links, which are necessary before channel assignment is launched.
- We provide a more comprehensive survey of different channel assignment approaches.

The remainder of this paper is designed as follows. Section 2 specified the channel assignment design issues. The link optimization approaches are discussed in Section 3. After that, we focus on channel assignment approaches. The classification of different approaches is shown in Fig. 1. In Section 4, we summarize the channel assignment approaches based on main channel assignment design issues, channel interference index, connectivity, routing, points out their advantages and limitations and makes overall comparisons on them. Section 6 presents the future research directions. Finally, Section 7 concludes this paper.

2. Channel assignment design issues

Enable the node to be work on different channels from the neighbor nodes will lead to increase the node capacity. However, it may cause several problems that degrade the network performance. In this section, we summarize the main design issues needed to be addressed by the channel assignment algorithm.

2.1. Connectivity

The channel assignment has been used as an effective tool to minimize the WMN interference and increase the capacity of the multi-radio wireless mesh network. The CA may remove some logical links from the original topology which may lead to network partition or an increased path length of some routing paths (Mohsenian-Rad and Wong, 2007). Fig. 2(a) shows that assigning the interface to one common channel can provide connected network, but it increases the total network interference. In contrast, Fig. 2(b) shows zero interference, completely eliminated the interference, and the links can be simultaneously active, but it causes network partition, for example, node *b* loses its connection with node *d*. Thus, the channel assignment should minimize total network interference while maintaining the network connectivity as shown in Fig. 2(c). From discusses above, there is an inverse relationship between the node connectivity and minimize the interference as illustrated in Fig. 2 (Skalli et al., 2007). Minimizing the total network interference is very important for CA algorithms,

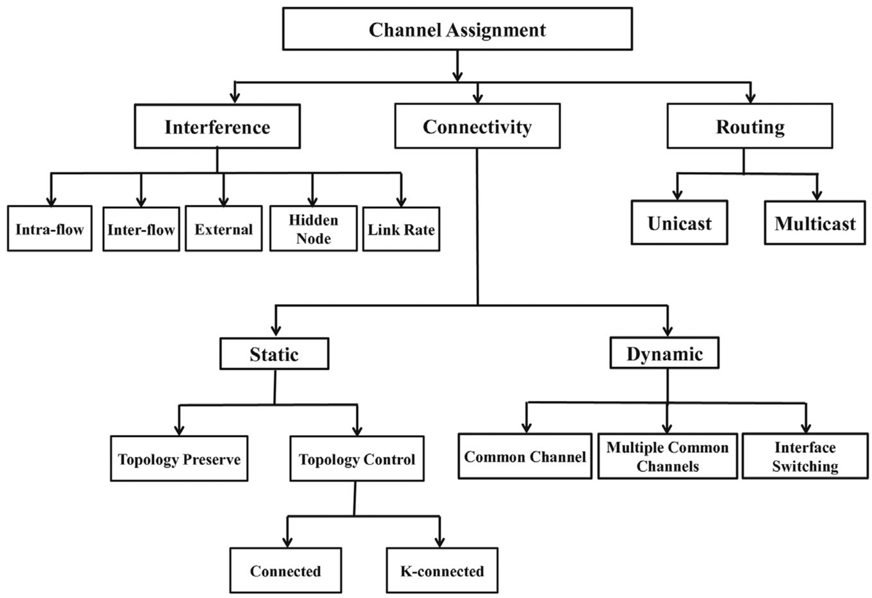

Fig. 1. Classification of channel assignment approaches for MR-WMN.

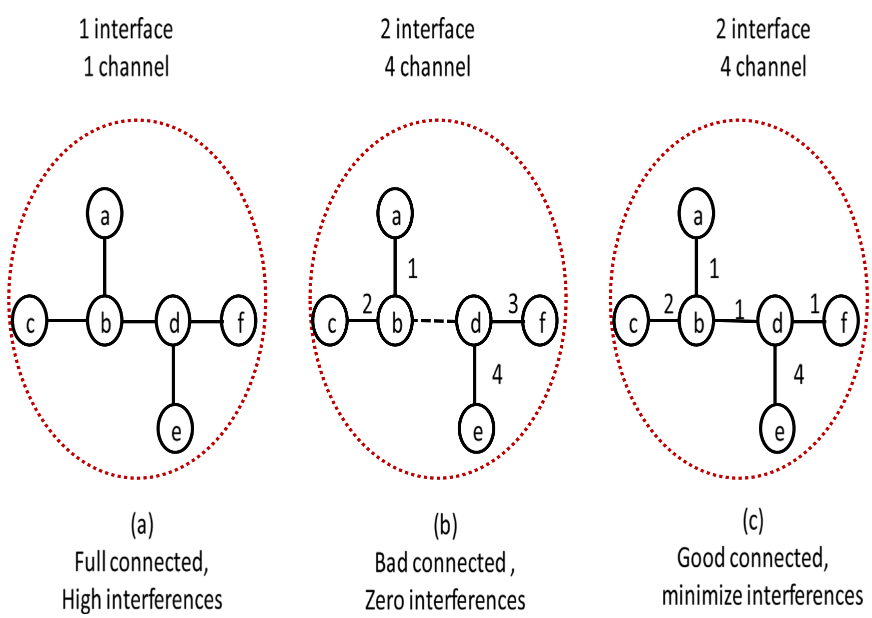

Fig. 2. Trade-off between interference and connectivity.

which mainly tries to maximize throughput and the capacity of WMN. Additionally, while taking into account minimization of the interference, we need to consider another important issue called network connectivity. On the other words, the channel assignment approach chooses the feasible channel assignment; it has to ensure that the channel assignment will not result in network partition.

2.2. Routing

The designing of an effective channel assignment for interference avoidance required knowledge about traffic load for each link. The routing protocol can determine the total traffic load carried by each link in WMN which is the main factor of the traffic-aware channel assignment approaches. On the other hand, the routing decision depends on the network connectivity and the effective capacity of each link which depend on the result of CA. Besides, The network connectivity is determined by how the nodes are connected to each other which depends on the result of channel assignment. Thus, the channel assignment has a direct impact on the routing decision, which may increase the path length of some routing paths. Therefore, routing and CA should be jointly optimized for MRMC WMN to minimize the interference dynamically and balance the traffic load among the different channels.

2.3. Stability

In distributed channel assignment algorithms, individually, each node selects a channel based on channel information of k-hop neighbor nodes. However, it is possible that two nodes select a same channel at the same time and then switching back because this channel is now overloaded. This could happen because of channel assignment may take a decision based on dynamic channel interference index such as traffic load. Another problem, when the channel of every node in the path is changed.

This happens due to the node under consideration finds that the selected channel by the previous hop is not the optimal channel anymore. Therefore, it selects a new channel on behalf of the previous hop, and the situation may repeat for all k-hops nodes on the established path, we refer the reader to paper (Raniwala and Chiueh, 2005) for more details about the ripple effective problem.

2.4. Mesh client issues

The mesh client node can join and leave the mesh router dynamically. As the mesh client moves from an old mesh router and becomes close to a new mesh router, it should join the new mesh router. The process involves handoff steps and switches its interface to the channel associated with the new router. This new connectivity needs to establish a new route with a new channel in order to continue receiving the data. To minimize the handoff issues of the mesh client need to find a proper network connectivity with less re-routed traffic. Other issues that need to be considered during the channel assignment is the number of mesh clients and the aggregated traffic load generated by the mesh clients at each mesh router.

2.5. Fault tolerance

Despite the fact that the WMN nodes are stationary and no power constraint is needed, a node may fail due to the hardware or software problems. Moreover, a link can also break because of temporary obstacle or co-allocated interferences. Hence, the channel assignment should address the fault tolerance in such that when a link or a node is failed, the network does not suffer from the network partition and can work in self-healing fashion. However, in multi-radio wireless mesh network where each node equipped with multiple radio, integrated the channel assignment with the fault tolerance issue become complex problem. This is because the channel assignment needs to select one link among the availability of multi-links per two nodes in such way that obtain the optimal solution.

3. Link optimization

In a multi-radio WMN, each interface is assigned a unique channel in the IEEE 802.11a/b/g bands. The IEEE 802.11b/g and IEEE 802.11a bands define three and twelve non-overlapping channels (frequencies), respectively. Distributing the limited number of channels among all logical topology links will lead to increase the number of the logical links that operates on the same frequency channel. Interference among neighboring links significantly reduces their effective capacity as the number of links operates in the channel is increased. The problem seriously affects the network capacity when the number of nodes increases or there are few channels. Therefore, link optimization, minimizing the total number of logical topology links, becomes necessary before channel assignment is launched. In literature, there are five approaches have been proposed for link optimization. In this section, we give a brief overview of link optimization as follows.

3.1. Spanning tree link optimization approach

The spanning tree approach constructs the logical topology based on the gateway paths. Periodically, a gateway sends its advertisement message and each node received the message will select the best path to the gateway and rebroadcasts the message to its neighbor nodes. Fig. 3(a) shows the single channel logical topology while Fig. 3(b) shows the final logical topology based on the spanning tree topology construction. Once the spanning tree is constructed, a heuristic channel assignment is applied to efficiently distribute the limited non-overlapping channels among the

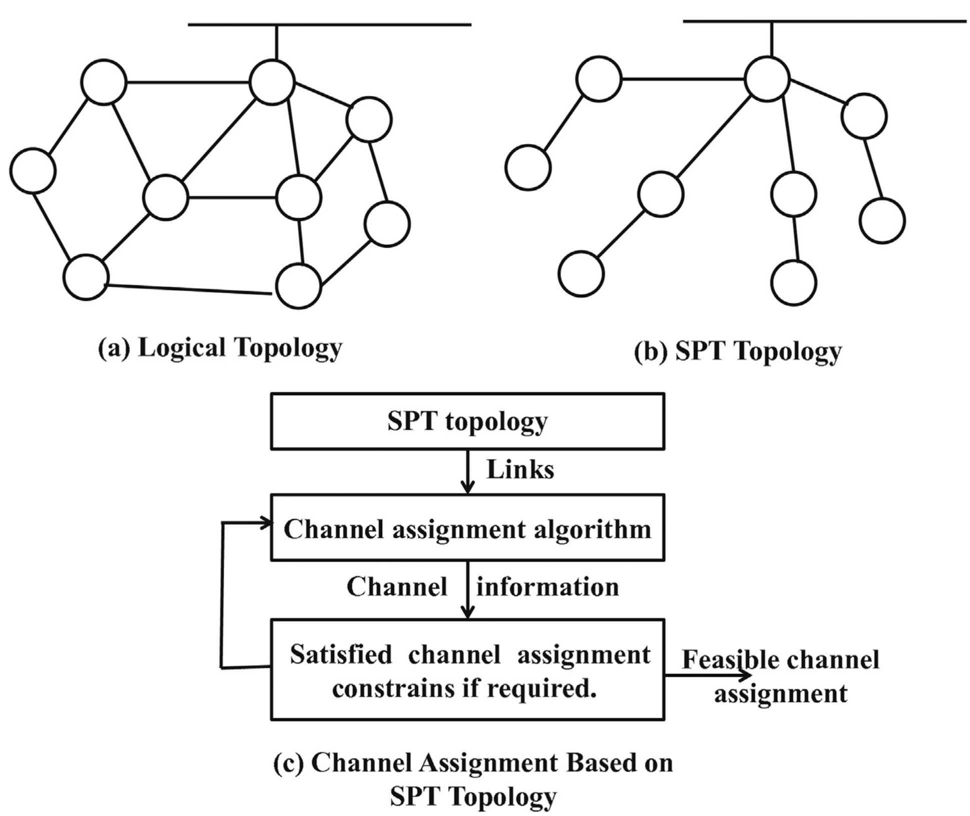

Fig. 3. Spanning tree link optimization.

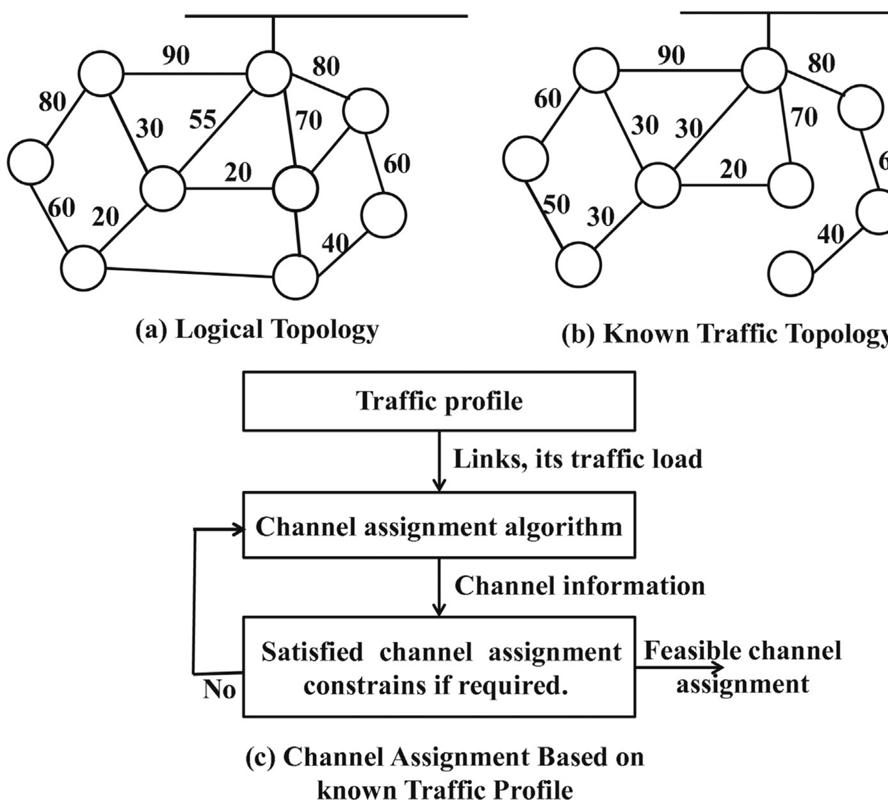

Fig. 4. Known traffic profiles link optimization.

links, see Fig. 3(c). On the other word, the channels are distributed among the links that form the gateway paths regardless of whether the links have a traffic or not (Raniwala and Chiueh, 2005; Kim and Suh, 2010; Kim et al., 2011).

3.2. Known traffic profiles link optimization

This approach records the traffic load of each link in the logical topology and constructs the logical topology according to the link load (Skalli et al., 2007; Subramanian et al., 2007; Avallone and Akyildiz, 2008; Riggio et al., 2011). Hence, the link that does not have traffic will be removed from the logical topology, see Fig. 4 (b). After that, a heuristic channel assignment approach can be used to efficiently distribute the non-overlapping channels among the constructed logical topology links as shown in Fig. 4(c).

3.3. Flow-based link optimization

The approach distributes the channels among the nodes involving on the established path. Once the node receives a route request message, it uses a channel assignment algorithm to select a channel from the non-overlapping channels. Once the node receives the route reply message, it switches one of its interfaces to the selected channel, Fig. 5. Fig. 5(a) shows the logical topology with four flows start from nodes *a*, *d* and *h*, respectively, toward the gateway. Fig. 5(b) shows the flow-based link optimization logical topology while Fig. 5(c) shows the flow-based channel assignment. The advantage of this approach is that channels are distributed only to the active nodes, the nodes that have traffic (Chiu et al., 2009; Mogaibel et al., 2012).

3.4. Power control link optimization

The basic idea of power control is to remove undesired links from the logical topology by using power control at each mesh router. Basically, each mesh router collects the information about its neighbors through hello messages and stores in neighbors table (NBT). Moreover, each router sends the NBT to gateway node and the gateway constructs the logical topology from the NBT by selecting the nearest neighbors for each node in the network (Chaudhry et al., 2012). The constructed logical topology, Fig. 6 (b) is used as the input to the channel assignment algorithms, see Fig. 6(c).

3.5. High quality metric link optimization

The approach is proposed to optimize the spanning tree logical topology by construct the spanning tree topology based on a high-quality metric such as Expected Transmission Time (ETT) (Draves et al., 2004), instead of using hop count. By using the high-quality metric to construct the spanning-tree logical topology, the links with low rate will be removed from the spanning-tree logical topology. As a result, minimizing the effectiveness of low-rate links on the ongoing transmission of high-rate links.

Fig. 7(b) and (c) shows the hop count and high-quality spanning tree logical topology, respectively. The number of low-rate links is three and one for the hop count and high-quality spanning-tree logical topology, respectively. The channels are distributed only to the links involving on the high-quality spanning-tree logical topology, Fig. 7(d).

4. Description and comparison of CA approaches

In this section, we describe and compare the CA approaches based on our classification presented in Section 1. For these approaches, we find out their basic ideas, advantages, limitations and make comparisons in each category. Also, in the end, a comprehensive table that compares all the CA approaches based on their basic properties is given. In general, the common notations used in

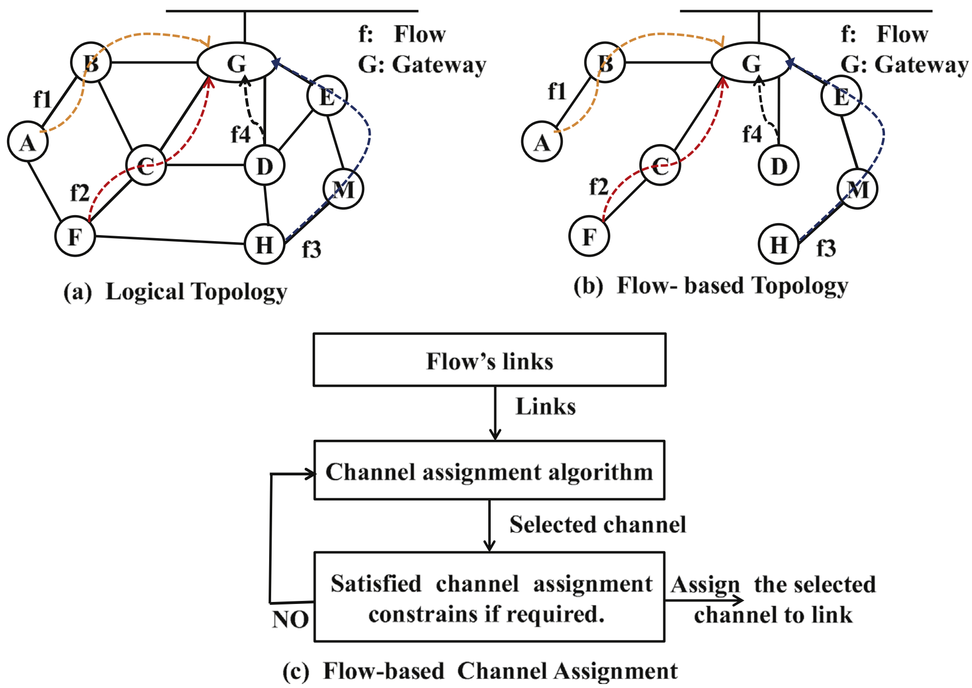

Fig. 5. Flow-based link optimization.

to compare and describe the CA approaches have been listed in Table 1.

4.1. Channel interference index

In a multi-hop wireless mesh network, there are five different types of interference that affect the network performance as shown in Fig. 8.

The intra-flow interference refers to the interferences between two consecutive links of a single-flow multi-hop path works on the same channel. In such case, the intermediate nodes cannot simultaneously receive and send data. The inter-flow interference occurs when two links belong to different flows using the same channel. Hence, both flows cannot transmit simultaneously over the links. The third interference is the external interference which refers to the interference caused by the network devices which are not under the control of the network operator utilizes the same frequency band. The fourth interference is the interferences results

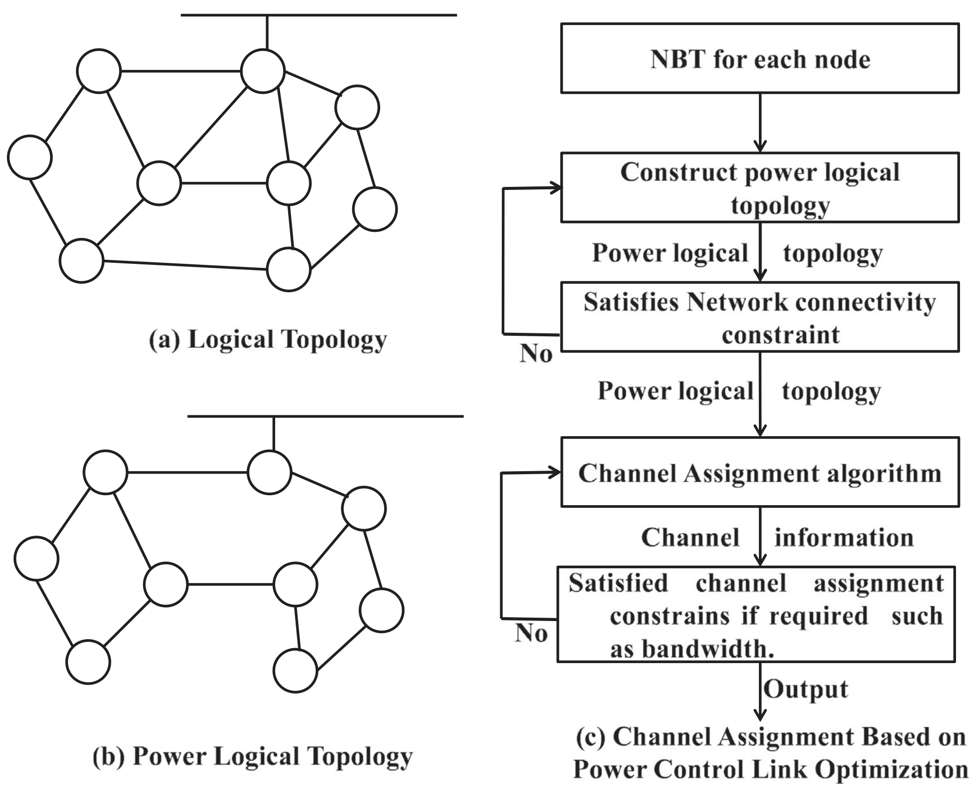

Fig. 6. Power control link optimization.

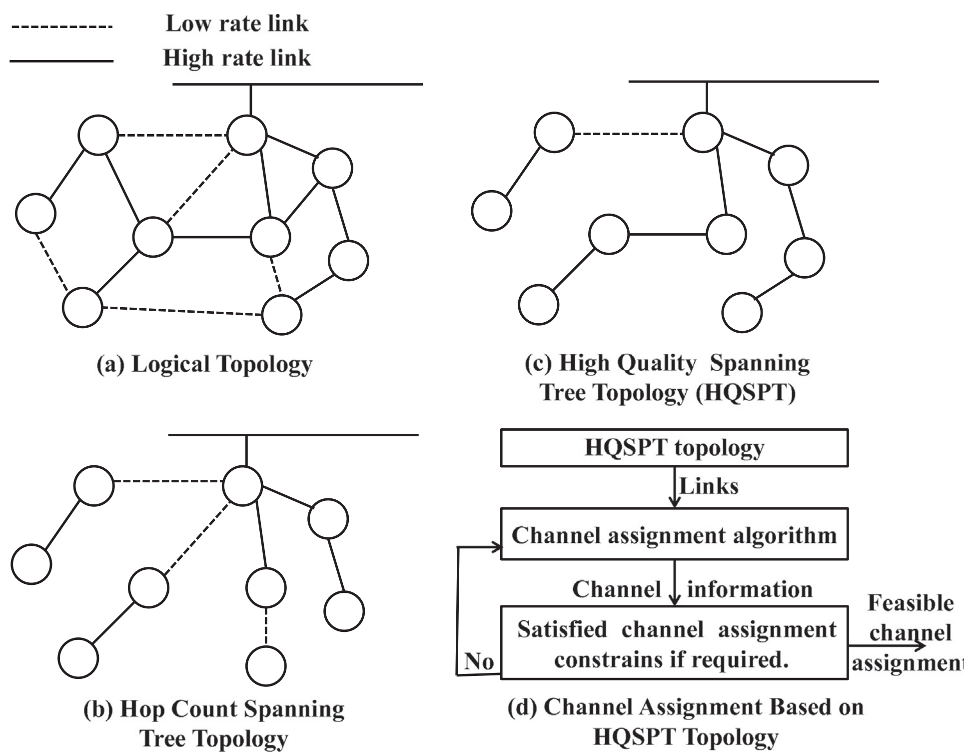

Fig. 7. High quality metric link optimization.

Table 1
Common notations used in to compare and describe the CA approaches.

Notation	Meaning
IntraFI	Intra-Flow Interference
InterFI	Inter-Flow Interference
ExtI	External Interference
LocalTrI	Local Traffic Interference
ChI	Number of channels
PC	Power control profile
TLoad	Traffic load
LDR	Link data rate
UDG	Unit Disk Graph
TPresv	Topology preserve
K-conn	*K*-connectivity
BW	Bandwidth
FlowR	Flow rate
Cong	Congestion
CG	Conflict Graph
Intf	Interface
MRCG	Multi-Radio Conflict Graph
LC	Link Capacity constrain
Conn	Network Connectivity

from collisions between transmissions by a node such as *A* which cannot hear the ongoing transmissions to its corresponding node *B*. The last interference is caused when there is at least one node with a lower rate, the throughput of all nodes transmitting at the higher data rate is degraded below the level of the lower data rate (Niranjan and Pandey, 2006). In this section, we categorize the channel interference index for channel selection as follows:

- *Interference-aware*: The basic idea of this method is calculating the number of the nodes/links in each channel. As well, a channel with the least number of nodes will be selected as a recommended channel. Hence, the main objective of the interference-aware channel assignment is to minimize the total network interference which refers to the number of the nodes/links sharing the same channel frequency. Many approaches model the interference within the interference area based on protocol model (Subramanian et al., 2006, 2007; Riggio et al., 2011; Mogaibel et al., 2012; Chaudhry et al., 2012; Devare, 2014; Revathi and Deva Priya, 2014; Gong et al., 2009; Yuan et al., 2012; Zhou et al., 2012; Tang et al., 2005) or physical model (GAlvez and Ruiz, 2013; Glvez and Ruiz, 2015; Shin et al., 2006; Rad and Wong, 2006). Some of the interference-aware channel assignment approaches aim to minimize the number of the links in the conflict graph sharing same channels has been proposed in Subramanian et al. (2006), Subramanian et al. (2007), Devare (2014), Revathi and Deva Priya (2014). Other interference-aware approaches minimize the number of links sharing the channel within the corresponding node's interference range (*k*-hops) (Riggio et al., 2011; Mogaibel et al., 2012; Chaudhry et al., 2012; Gong et al., 2009; Yuan et al., 2012; Zhou et al., 2012; Tang et al., 2005).
A more realistic interference index is used in (Subramanian et al., 2006; Revathi and Deva Priya, 2014). In Subramanian et al. (2006), periodically, each node measures the external interference of each channel through the Radio Frequency Monitoring mode (RFMon) (Jardosh et al., 2005). In RC-BFS (Revathi and Deva Priya, 2014), the reality check mechanism merges the physical interference model with the protocol model to overcome the inaccuracy of the protocol interference model used in BFS-CA algorithm. The mechanism reverses the obtained interference's result of the protocol model to obtain a feasible solution based on the known scheduling and power control information. The proposed interference model captures the accuracy of the physical model, besides it ensures the simplicity of the protocol model by developing reality check mechanism.
- *Traffic-aware*: Unlike the interference-aware channel assignment, the traffic-aware CA distributes the channels among the links based on the channel load. In Subramanian et al. (2007), Sridhar et al. (2009), the proposed metric calculates the sum of traffic loads over all interfering links in a WMN. This metric can

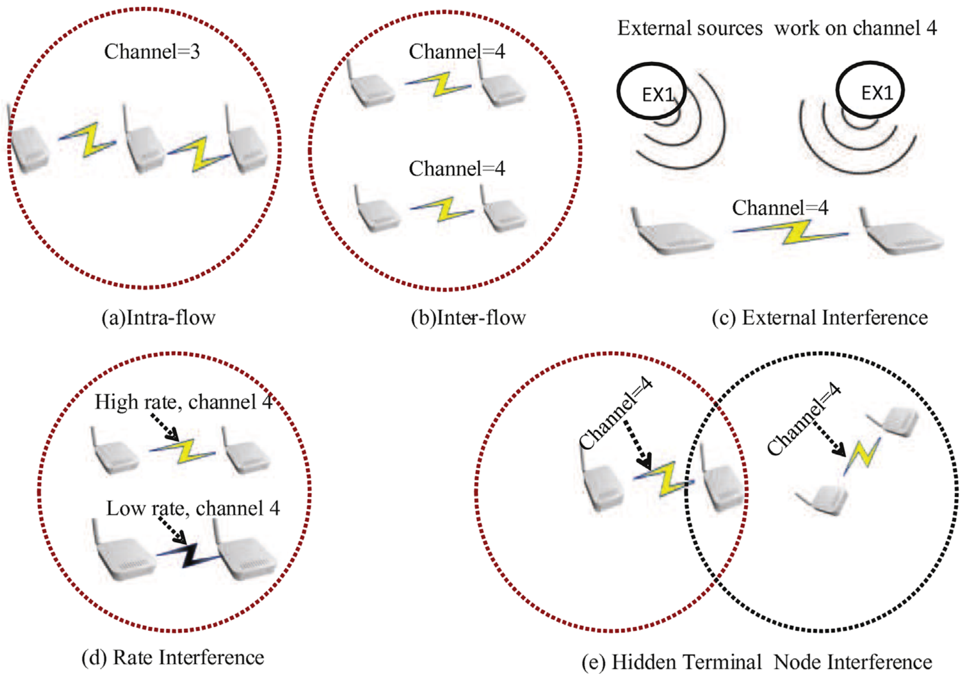

Fig. 8. Types of the interference.

be calculated as follows:

$$index = \sum_{j=1}^{k} usage(j, c) \tag{1}$$

where k is the interference range and the $usage(j, c)$ is the channel usage table. The channel usage table is maintained at each node to keep track of the amount of data sent by node j over the channel c.

In Chiu et al. (2009), the protocol model is enhanced by considering both traffic load carried by the channel and the path loss. The path loss can capture the impact of the distance on the SINR which inversely proportional to the distance from the node under consideration. The proposed channel index can be calculated as follows:

$$index = \sum_{j=1}^{k} \frac{usage(i, j)}{j^{y}} \tag{2}$$

where y is the path loss exponent, and $usage(i, j)$ is the channel usage table. The channel usage table is maintained at each node to keep track of the amount of data sent by node j over the channel i.

In LA-CA (Raniwala et al., 2004), the links are sorted in descending order of their traffic load, whereas, the MesTic (Skalli et al., 2007) sorts the links according to ranking formula. The formula does not consider only the traffic load, but also the distance of the link from the gateway and the number of interfaces per nodes.

$$\text{Rank(node)} = \frac{Traffic\ load(node)}{Distance(node)*Number\ of\ interfaces(node)} \tag{3}$$

The CRB-CA (Sarasvathi and Iyengar, 2012) was proposed to enhance the MesTic ranking formula by including the link quality in addition to the link load (*WCETT*), distance and the number of interfaces:

$$\text{Rank(node)} = \frac{WCETT(node)}{Distance(node)*Number\ of\ interface(node)} \tag{4}$$

In Athanasiou et al. (2011), the authors proposed a centralized load-aware channel assignment that takes into account the load carried by the access point in terms of channel condition, the number of associated users and communication load. In Mohsenian Rad and Wong (2009), Bakhshi et al. (2011), traffic-aware channel interference has been proposed based on the channel load where a channel with least traffic load is selected to resolve the congested links. In Mohsenian Rad and Wong (2009), each node monitors the traffic load of ongoing links. Once the node detects that one of its ongoing links becomes congested, it resolves the congested link by switching its corresponding interfaces for both link's nodes to the least load channel. In Bakhshi et al. (2011), a central node monitors the feasibility of the established path. If the path is not feasible, at least there is one link is congested, the node determines the bottleneck links along the path and assigns them with the least load channels.

- *Throughput-aware*: In Shin et al. (2006), the sum of the end-to-end throughput of all existing flows is proposed as channel selection index to guarantee fairness among all flows in the WMN. In Raniwala et al. (2004), a cross-section goodput is proposed for channel selection where the approach computes the sum of effective achievable throughput in the WMN. This metric is used to maximize the total throughput between all pairs of nodes in the network. Another approach (Raniwala and Chiueh, 2005) uses this metric to maximize the sum of throughput overall pairs between a normal node and a gateway node in the network.
- *QoS-aware*: In Kumar and Lee (2015), Pounambal and Krishna (2016), the packet drop and blocking probability has been used to compute the performance of the channel and a channel with minimum probability is selected as recommended channel. The metric is used to reduce the delay in the channel and ensure the ongoing transmission is completed without interruption delay. In Chen et al. (2007), the airtime cost metric is used for channel selection where a channel with minimum airtime will be selected as recommended channel. This metric is calculated based on the channel access overhead, packet error rate and link transmission rate. This metric can maximize the end-to-end throughput in wireless multi-radio mesh networks. In GAlvez

and Ruiz (2013), the packet error rate with existing of simultaneous flow transmission and ambient noise was used as channel selection metric. This metric can model the interference in the real environment. In Lin and Zhuang (2013), the node delay constraint is used as channel selection metric. Thus, a channel with minimum total interference and satisfies the node delay constraint for the received request will be selected as a recommended channel. In Chakraborty (2015), path end-to-end delay is proposed for channel selection. This metric can avoid the interference and collision by choosing a long path that satisfies the delay bound tree.

- *Capacity/data rate aware*: In Rad and Wong (2006), the authors proposed capacity aware channel selection based on the sum of actually achieved link capacity. It calculates the sum of actual achievable link capacity in a WMN by considering the congestion over all links. This metric indicates the global impact of a certain channel assignment. In Mohsenian Rad and Wong (2009), Bakhshi et al. (2011), the available bandwidth channel selection metric is proposed for channel selection where the channel is assigned to the link based on the available bandwidth. The metric is calculated based on the total channel load and the physical link capacity. This metric is used to ensure that the physical capacity of link l is sufficient to carry the traffic load passed through it. However, all the interference-aware and traffic-aware channel interference index may not work well in multi-rate multi-channel multi-radio WMN due to their assumption that each link has fixed rate. Hence, the channel interference index which takes into account the interference caused by the low rate links on the high data rate links has been proposed by Kim et al. (2010, 2011), Niranjan et al. (2006). The channel interference index of channel c, where c belongs to set of non-overlapping channels, can be computed as follows.

$$index = \frac{1}{\sum_{(u,v)\in K} \frac{1}{R_{uv}}} \quad (5)$$

whereby the R_{uv} is the data rate of the link connected the node u with node v and the nodes $u, v \in K$-hop interference range of the node under consideration.

- *Summary of the channel interference index*: Most of the channel assignment approaches proposed their own channel interference index to optimize their channel selection decision in order to minimize the total network interference. The channel interference metric can be categorized into four types -interference-aware, traffic-aware, capacity/data rate-aware, QoS-aware and throughput-aware.

Many CA approaches (Subramanian et al., 2006; Chiu et al., 2009; Mogaibel et al., 2012; Subramanian et al., 2007; Zhou et al., 2012; Ramachandran et al., 2006; Sen et al., 2007; Naveed et al., 2007; Shui and Shen, 2008; Chen et al., 2009; Dhananjay et al., 2009; Pediaditaki et al., 2009; Jahanshahi et al., 2013; Cheng et al., 2013; Athota and Negi, 2015) efficiently address inter-flow interferences in their channel interference index. However, only few research studies address the impact of the interference caused by the hidden nodes (Zhou et al., 2012; Mogaibel et al., 2016), multi-rate link sharing problem (Niranjan et al., 2006; Kim and Suh, 2010; Kim et al., 2011) and external interference (Subramanian et al., 2006; Naveed et al., 2007) on the channel throughput in their channel interference index. Several channel interference indexes are developed based on the link capacity (Raniwala et al., 2004; Raniwala and Chiueh, 2005; Subramanian et al., 2007; Rad and Wong, 2006; Sridhar et al., 2009) in their channel interference index to ensure load balancing in WMN. However, a few of them use the channel capacity instead of link capacity to balance the traffic load over the available non-overlapping channels. Finally, the QoS-aware channel interference index utilize the end-to-end delays and link quality to ensure high-speed transmissions over WMN. However, Only few approaches explicitly consider switching delay (Kyasanur and Vaidya, 2006) and queuing delay (Naveed et al., 2007; Kyasanur and Vaidya, 2006) in their indexes.

4.2. Connectivity-aware channel assignment

As discussed in Section 2, there is an inverse relationship between the node connectivity and minimize the interference. The network interference can be decreased by removing some of the links from the logical topology (Mohsenian-Rad and Wong, 2007). However, this may cause network partition or increase the path length of some routing paths. Therefore, the channel assignment approach should ensure that the channel assignment will not result in network partition. Currently, there are two channel assignment approaches have been proposed to find a reasonable and flexible solution between the connectivity and interference. That is dynamic channel assignment and static channel assignment.

4.2.1. Node connectivity in dynamic channel assignment

The dynamic channel assignment assigns the channels to interfaces for a period of time and a node can switch to a new channel according to channel status. In the dynamic channel assignment, the node connectivity is addressed by either using single common channel (Chiu et al., 2009; Gong et al., 2009; Yuan et al., 2012; Zhou et al., 2012; Bakhshi et al., 2011; Pathmasuntharam et al., 2004), multiple common channels (Mogaibel et al., 2012; Naveed et al., 2007), or interface switching mechanism (Kyasanur and Vaidya, 2006; So and Vaidya, 2004; Li and Feng, 2010; Ding et al., 2009, 2013).

In the single common channel, one interface works on a fixed common channel, where the broadcast and control messages are sent through this interface. In Chiu et al. (2009), Gong et al. (2009), Yuan et al. (2012), Pathmasuntharam et al. (2004), one interface is fixed as a control interface while the others are considered as data interfaces. The control interface is assigned to a common channel for all nodes to keep the network connectivity and to carry the control messages. The data interfaces are considered as sender and receiver interfaces. The receiver interface is assigned to a unique channel for receiving data, whereas, the sending interface can switch between channels according to the number of the flows received at the node. In PCAM, the receiving interface is considered as static and assigned during the network plan while in Chiu et al. (2009), Gong et al. (2009), Yuan et al. (2012), Zhou et al. (2012), both receiving and sending interface considered as dynamic interfaces and assign a channel during the routing discovery process. This approach keeps high network connectivity but it suffers from control channel interference and congestion in a high-density network.

The multiple common channels approach has been proposed to overcome the limitation of using the single common channel. The simplest way of static interface assignment is the Common Channel Assignment (CCA) (Draves et al., 2004). In CCA, the radio interfaces of all nodes in the network are assigned to common channels. In Mogaibel et al. (2012), the author proposed a cross-layer reactive channel assignment to reduce the interface switching overhead without the need to modify the MAC protocol. The proposed solution classified the interfaces as static and dynamic based on the node types, local nodes (inactive) and gateway nodes (active). Initially, all nodes are considered as an inactive node and assign their interfaces to common channels. Once the node receives a routing reply message from the gateway, it selects channels (at least one channel) and become active nodes. The inactive node can communicate with its inactive nodes through one of its predefined common channels. Moreover, the active node keeps at least one interface works on a predefined common channel to ensure the node connectivity. This channel is selected based on the neighbor's active nodes and different from local channels used at the interference range. However, As seen from step 6, channel selection step, where the gateway randomly assigns channels to the received flow; hence more accurate channel assignment metric is needed such as physical or protocol model;

Cluster-based channel assignment strategy has been proposed to address the node connectivity for dynamic channel assignment. In the cluster-based channel assignment, the nodes are classified into different clusters and a fixed channel is assigned for each cluster with aims to minimize the inter-cluster interference (Naveed et al., 2007). However, the cluster-head and relay nodes become the most bottleneck nodes since all multi-hop traffic must pass through these nodes to the indeed destination.

Different from the common channel/channels strategies, the interface switching strategy allows any interface to be assigned to any channel, and interfaces can frequently switch from one channel to another (Subramanian et al., 2006; Shui and Shen, 2008; Dhananjay et al., 2009; So et al., 2004). Therefore, a network using such a strategy needs some kind of synchronization mechanism to enable communication between nodes in the network.

In So et al. (2004), a Slotted Seeded Channel Hopping (SSCH) mechanism has been proposed for multi-interface multichannel wireless network, but it utilizes a distinctive approach for channel synchrony. In the SSCH, each node switches channels synchronously in a pseudo-random sequence so that all neighbors meet periodically in the same channel. However, such mechanism may require all nodes to periodically visit a predetermined rendezvous channel to negotiate channels for the next phase of transmission (So et al., 2004).

In So and Vaidya (2004), Li and Feng (2010), the time is split into control period and data period. In the control period, all nodes shift to a default channel to connect channels to be utilized in the data period. In the data period, nodes switch to the negotiated channels to send data. If the node received a broadcast packet in data slot, it buffers the broadcasting message until the next BS slot.

In Kyasanur and Vaidya (2006), one interface is considered as a fixed interface, while the remaining interfaces are considered as switchable interfaces. The fixed interface is assigned a fixed channel for a long period of time while the switchable interfaces can frequently switch from one channel to another. Each node can change its fixed channel only if the current channel is not the best channel and the node probability equals to 0.4. To keep the network connectivity, the protocol broadcasts the control messages over all available channels by switching the dynamic interface among all channels. However, such approach suffers from high interface switching cost due to broadcast the control message through all available channels. In a high-density network, the interface switching becomes very high which may limit the network performance.

In Ding et al. (2009, 2013), the authors proposed Adaptive Dynamic Channel Allocation protocol (ADCA) which classified the interface based on the network links as static and dynamic links. The static links are constructed based on the spanning tree structure, so, all links in the spanning tree should be assigned with static channels, while the links which are not included in the spanning tree topology considered as dynamic links. Hence, when a node wants to communicate with other nodes, it looks in the routing table to see whether the connected link with next hop is a dynamic or static link. If static, the packet is sent over the corresponding static interface. Otherwise, the packet is sent over a dynamic interface by switch the interface to the next hop's fixed channel.

In general, the interface switching mechanism has higher overhead than the static mechanism due to frequent interface switching between channels. Furthermore, the frequent interface switching mechanism depends on traffic load and link stability. Such frequent switching increases as the traffic load increases which in turn increase the packet latency and degrades the network throughput. The static common interface may become a performance bottleneck problem in the high-density network since all WMN nodes using a single common channel to broadcast the control message which in turn increases the probability of packet collision caused by hidden nodes.

4.2.2. Node connectivity in static channel assignment

In the static channel assignment, the node connectivity is preserved by ensuring that each node shares a common channel with its neighbors during the channel assignment stage. However, deciding which nodes can communicate with the network can affect the network performance. Consequently, it may increase the length of the routes between nodes and it arises the network partitions due to the inability of different neighbors to communicate with each other unless they assign a common channel. Therefore, a number of approaches have been proposed to address the node connectivity by solving the channel assignment and topology control jointly. In this section, we review different channel assignment approaches that formulated the node connectivity as a joint of the channel assignment and topology control problem.

- *Centralized Tabu-based Algorithm* (*CTA*): In Subramanian et al. (2007), the authors formalized the channel assignment problem as a conflict graph problem with aims to minimize the interference while keeping the k-network connectivity. The K-connectivity refers to each node connected with only k nodes that keep the node connected with all network nodes after channel assignment. Hence, the number of the edges in the conflict graph shall be minimized. The conflict graph is divided into $k - max$ partitions based on maximizing the number of the edges that belong to more than one partition. Then, a heuristic Tabu-search algorithm is proposed to distribute the channels among each partition nodes. The Tabu-search technique is used to look for a feasible solution to the problem without considering the interface constraint. Moreover, it starts from a random feasible solution and creates a better solution at each step in an attempt to reach a good solution in the end. After that, the algorithm checks the feasible solution based on the interface constraint by a repeat color merging algorithm. For each mesh node that has been assigned more colors than its number of interfaces, two of its colors are merged into one color and the changes may broadcast to neighboring nodes.

  The advantage of CTA as shown by the authors is that it achieves very nearby results to the lower bound of the total network interference. However, since the algorithm assigns the channels to the vertices which implies that only one link can be modeled between each pair of nodes, its main limitation is that the algorithm fails to model the availability of multi-links between two pair of nodes in order to efficiently utilize the availability of multi-radio per mesh router.

- *Breadth First Search Channel Assignment* (*BFS-CA*): The BFS-CA is developed by Subramanian et al. (2006) with aims to minimize the inter-flow and the external interferences in the multi-radio multi-channel WMN. In BFS-CA, periodically, each node measures the external interference through the Radio Frequency Monitoring mode (RFMON) (Jardosh et al., 2005) and then sends the collected information to the Central Server (CAS). After that, the CAS constructs the multi-radio conflict graph (MRCG) based on the above information and uses it as input to the channel assignment algorithm. The CAS starts by assigning a default channel to each mesh router with aims of keeping the network connectivity and minimizing the interference with the external co-located wireless networks. Then, it runs the BFS algorithm to distribute the channels among remaining interfaces of each router. Since the links close to the gateway may carry more traffic, the BFS-CA gives higher priority in selecting channels to the links starting from the gateway. Finally, the feasible channel assignment is sent back to each mesh node. To adapt the algorithm to the changing in external interferences, the CAS periodically computes the feasible channel assignment. In Devare (2014), the authors proposed an enhancement of BFS-CA channel assignment named as Autonomous network Reconfiguration System Channel Assignment (ARSCA). The ARSCA integrates the BFS-CA with autonomous network reconfiguration system with aims to reassign the failure links before moving to rerouting the link's flows. So whenever a link failure occurs, the gateway recomputed the channel assignment, based on BFS-CA, according to collected channels information. Moreover, another enhancement made on BFS-CA (Subramanian et al., 2006) called Reality check BFS channel assignment (RC-BFS) developed by Revathi and Deva Priya (2014). In RC-BFS, the reality check mechanism merges the physical interference model with the protocol model to overcome the inaccuracy of protocol interference model used in BFS-CA algorithm. The advantages of the BFS-CA algorithm mainly include its MRCG can model the multi-link case and it is the first approach take into account the external interference. However, the BFS-CA based channel assignment approaches have the following three limitations:

1. As seen from step 5 of the BFS-CA approach, minimizing the external and internal interference by combining the MRCG and the channel ranking is intuitive, combining the MRCG and the channel ranking may not offer known bound for the worst-case performance.
2. It is only suitable for the multi-radio multi-channel WMN where a gateway acts as the central point of the network traffic.
3. Since the algorithm can adapt to the change in external interferences, the channel switch may occur frequently. Consequently, it increases the latency which may limit the total network throughput.

- *A topology control approach for utilizing multiple channels in multi-radio WMN*: In Marina et al. (2010), the authors proposed a greedy polynomial-time heuristic channel assignment algorithm called "CLICA" to find connected and low interference topologies. Initially, each node is given a flexibility based on some criterion (e.g., distance to the gateway, traffic load) to determine the default order for making channel assignment decisions. The node flexibility referred to a set of channels that a node can select from without partition the network connectivity. Fig. 9(a) shows the single channel connectivity graph and each link label with its traffic load. We assume nodes a and c has a single radio while the other nodes provide with two radio interfaces. Based on the traffic load criterion, the default order will be as follows $a-b, b-c, d-f, e-d, d-v$. In the link traffic load channel assignment, the link order cannot override during the execution time which may result in partition network as shown in Fig. 9(b). In CLICA, the link order may override during the execution time based on the node flexibility, Fig. 9(c). For example, suppose the CLICA starts at node a to color its incident links, it chooses $c1$ to color the link $a-b$. As a result, both node a and b lose further flexibility in choosing colors for their other incident links. So, CLICA additionally selects b to color its incident links and so on and reorders the links according to their flexibility as follows $b-c, b-d, d-f, d-e$. It recursively overrides the link order colors the link until all link is visited. However, since the number of radio interfaces at each node is difficult to model in the unit disk graph to distribute channels, an extra phase at the end of the algorithm is required to deal with the unassigned radios.
- *Interference Survivable Topology Control* (*INSTC*): Given the mesh network $G(V,E)$, the authors of Tang et al. (2005) formulated the channel assignment as a minimum interference survivable topology control problem (INSTC). The resulting is a logical topology with minimum network interference and guaranteeing that the topology is k-connected. To solve the INSTC problem, a heuristic algorithm has been proposed, which runs in polynomial time. By given the k-connected logical topology, a greedy heuristic channel assignment is used to allocate the available non-overlapping channels for links in the k-connected topology. The total interference of link e defined as the number of links that are within interference range of e. The major advantage of the INSTC algorithm is that it is a polynomial time algorithm that obtained a robust k-connected topology. Consequently, the algorithm gets better results than CLICA when the number of interfaces is small such as two or three. Due to its similarity with CLICA as shown above, its drawbacks are similar to those of CLICA.
- *TiMesh*: Mohsenian-Rad and Wong (2007) formulated the problem of joint topology control, CA and routing in WMN into a linear optimization problem. The TiMesh divides the joint problem into two sub-problems and separately solved into two stages. In the first stage, LInear Programming (LIP) is used to solve the joint topology control and channel assignment. The full connected single channel logical topology is selected as a

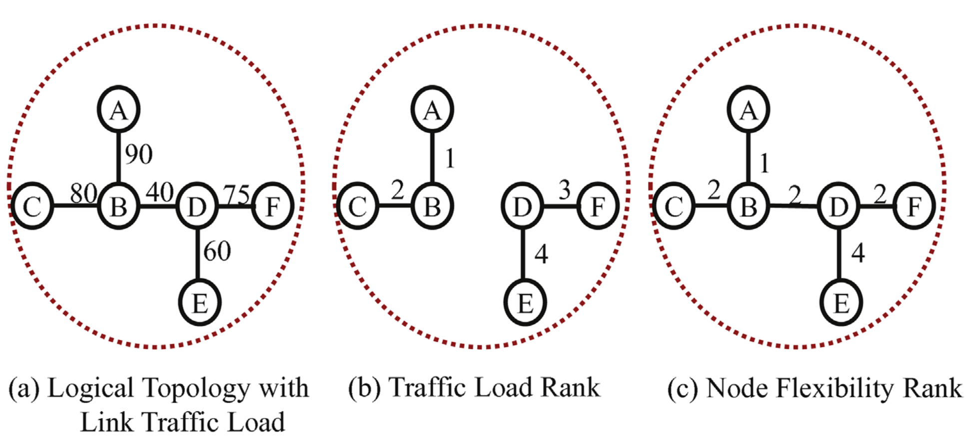

Fig. 9. Sample topology of two different CA: (b) LA-CA and (c) CLICA.

starting point and using LIP to construct the sub-optimal logical topology and channel allocation. The TiMesh used Iterated Local Search (ILS) (Lourenco et al., 2002) to find the sub-optimal solution instead of using LIP due to simple and efficient heuristic methods to find the sub-optimal solutions.

By given the sub-optimal logical topology, the interface and channel allocation assignment, the second stage starts to find a path from the source node to the destination based on capacity constraints. The main advantages of the TiMesh algorithm are that the adopted ILS approach is simple and efficient so that it can easily apply for small scale WMN. Moreover, since the proposed model considers the predictable traffic load between different source and destination pairs, the actual capacity of the logical links and the number of interfaces in mesh router, it provides the bottleneck links with a higher capacity. The major drawback is that use a greedy heuristic algorithm, such that the performance bound of the algorithm in the worst case is unknown.

- *Joint Topology Control, Power and Routing* (*JTCR*): This paper (Chen et al., 2007) proposed a joint routing, topology control and channel assignment to exploit both spatial reusability and channel diversity. The proposed approach, periodically, checks the channel utilization condition. If the channel overloaded condition is detected, the approach tries to find the best feasible adjustment candidate based on the Equivalent Channel Airtime Metric (ECATM). A candidate with smallest ECATM value is considered as a feasible adjustment candidate if it satisfies the following three constraints. First, it maintains the current throughput achieved by each flow. Second, it preserves the network connectivity. Finally, the adjustment of power levels should not cause asymmetric links.

  Assume that node *a* notices that the channel one is overloaded, hence, it triggers the adjustment candidate selection process. The procedure classifies the interfering links based on adjustment power level. Since each radio has two power levels that correspond to the transmission range of *R*2 and *R*1 e, there are two possible candidates -one with low power transmission range *R*1 and another with high power transmission range *R*2. Fig. 10(b) and (c) shows the conflict graph of both two candidates, respectively. By adjusting the power level of node *a*, *b*, *e* and *f* to the lower power level, both links *cd* and *ef* can concurrently transmit. Moreover, both links *ab* and *cd* interfering with each other due to both links located on the lower power level of each other, so the possible adjustment candidate can be channel adjustment, Fig. 10(d). However, node power adjustment may direct impact on routing which may require some nodes to change their routing.

  The advantages of JTCR can describe as follows. First, it is first approach that has addressed the problem of jointly the routing and topology control in multi-radio multichannel WMN network. Second, it efficiently utilizes the available non-overlapping channels by considering spatial reusability. Third, no modifications are required to the IEEE 802.11 MAC layer. However, the approach may fail to find a feasible candidate channel assignment result when applies to multi-hop density network or supports more than two power controls. Moreover, the channel and power adjustment may also bring about chain propagation (Chen et al., 2007).

- *Topology and Interference-Aware Channel Assignment* (*TICA*): The authors of Chaudhry et al. (2012) proposed a centralized topology and interference-aware channel assignment based on power control. The main idea is to remove the loose links from the logical topology and then applies the channel algorithm. The “select *x* less than *X*” topology control has been proposed with aims to maintain the network connectivity with small number of nodes. First, each node collects the neighbor's node information through broadcasting Hello message. The nodes information is stored on Power Neighbor Table (PNT) which sorted in ascending order based on their power. Then, the gateway constructs the direct neighbors table (DNT) for each node based on the select *x* less than *X* algorithm. After that, it calculates the minimum power required to reach each of nodes in DNT. Finally, it checks the network connectivity. If the result is not connected, it moves to next higher value of *x* and checks the connectivity again. Once the feasible result is found, the gateway distributes the channel among the remaining nodes

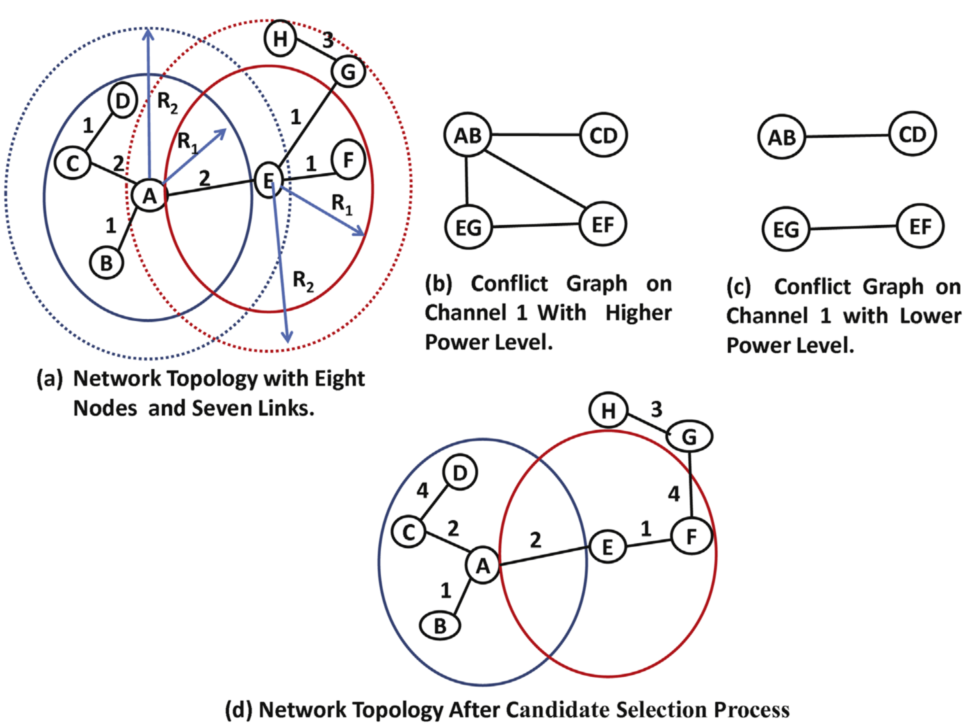

Fig. 10. An example to demonstrate adjusted schemes in JTCR routing protocol.

based on the least interference channels. The main objective of TICA is to minimize the inter-flow interference and keep network connectivity by adjust the transmission power for each radio interface to the minimum power. However, select x than x topology control may lead to network partition and links failure when there is node failure. Moreover,recomputing the TICA feasible channel assignment for every node failure will increase the algorithm complexity.

- *Discrete Particle Swarm Optimization Channel Assignment* (*DPSO-CA*): The authors of Cheng et al. (2012, 2013) proposed a centralized channel assignment algorithm based on the discrete particle swarm optimization. The DPSO-CA provides a population-based search for the optimization problem in which population individuals called particles change their position according to simple formula. The DPSO-CA starts by initializing the particle value with a feasible channel assignment that satisfies the topology preservation as well as the radio constraints. Simple way to ensure full network connectivity is assigned a common channel to all nodes. Then, each particle updates its position based on the crossover operation and mutation operation.
  The main advantage in addition to proposed discrete particle swarm optimization approach for channel assignment problem with subject to the interface and topology preserving constraints, it studied the impact of radio utilization on the fractional network interference. However, since the DPSO-CA preserves only single link between any two pairs node, some node interfaces not efficiently utilizes to increase the node capacity. Moreover, the algorithm assumes constant traffic load carried by each link, which makes the algorithm not practical for dynamic network.
- *Improved Gravitational Search Algorithm (IGSO)*: By given mesh network $G(v, e)$, a novel local search algorithm which is combined with the gravitational search algorithm (GSO) is proposed to find a channel assignment solution that minimizes the total network interference while keeping the network connectivity (Doraghinejad et al., 2014). In IGSO, its inputs are the number of radios, conflict graph and number of agents and its objective is to find the best channel assignment solution which minimizes the total network interference and keep topology connected. The authors define the total network interference as the sum of all links that are interfering with each other. Each good channel assignment candidate is considered as agent. Each agent continually computes its better position based on to its current velocity and acceleration and then updates its position with the new computed position.
  The IGSO, first, constructs the good CA solution from the inline agents and then applies the local search for integral programming to find the best solution. To find the best solution, the local search algorithm randomly selects a few nodes and for each selected node, DLS randomly changes a node's channels among the available channels. This algorithm minimizes the total network interference while keeping the network connectivity. However, the IGSO fails to efficiently utilize the multi-radio in order to increase the node capacity. Moreover, since the IGSO's DLS algorithm randomly select a few nodes, the algorithm may fails to find the best optimal CA solution.
- *Minimum shortest and interference disjoint path*: In Bao et al. (2014), a polynomial heuristic minimum shortest and interference disjoint path channel assignment named “MSITD” has been proposed to find an approximate k-connectivity network topology that satisfied the k-connectivity, interfaces, and capacity constraints. The k-connectivity, in this paper, refers to that there are k disjoint node paths between any two nodes in the network. The algorithm starts by finding the k-connected topology as the initial logical topology. In the next step, the approach solved the disjoint paths by utilizing the shortest path and prim's minimum spanning tree algorithm which can effectively reduce the logical links. The aim of this procedure is to minimize the sum of the interference link for each node in the WMN. After the k-connectivity disjoint path is constructed, priority channel assignment based on the minimum spanning tree search is applied for channel assignment. The main advantage of MSITD is that it provides better results with limited number of radios. However, its results show that the protocol does not efficiently utilize the channels and radio resources when there are multiple radio interfaces. In addition, since the MSITD increases the path length in order to minimize the interference, it may fail to guarantee the QoS constraints for the Qos's application.
- *Cluster-based topology control and channel assignment*: A semi-static cluster-based channel assignment approaches named ComTac (Naveed et al., 2007) and CBCA (Athota and Negi, 2015) have been proposed to minimize the aggregated interference and maintain the node connectivity. The approaches comprise of two stages: clustering and channel assignment. In the first stage, the WMN nodes are divided into fixed radius clusters based on the distance, in term of hop count, from the cluster head. After that, the spanner graph is utilized to remove the unwanted links such as links with higher interference. The next step is to apply the CA on the constructed topology. During the second stage, the ComTac allocates channels to default and non-default interfaces. It assigns a fixed channel to all cluster's nodes in order to keep the inter-cluster communication and proposed sum of channel utilization to allocate channels to non-default interfaces. However, the CBCA proposed varying channel assignment instead of using a common default channel. Besides, it differs from ComTac in the way of producing cluster and selection of cluster head. The ComTac produces produce 2-hop clusters while the CBCA produce 1-hop clusters in order to minimize the number of border nodes.
  The main advantages of ComTac can be described as follows: first, it maintains the inter-cluster connectivity using a default interface within a cluster and intra-cluster connectivity by border nodes. Second, it provides fault tolerance by constructing multiple paths. Third, it takes into account the both non-overlapping and overlapped channels resources, queuing delay and external interference. Finally, it can avoid the ripple effect problem by performing channel assignment only by the cluster heads.
  The advantages of CBCA over the ComTac, it maintains the inter-cluster and intra-cluster connectivity through the non-default channel assignment which in turn minimizes the inter-cluster interference. In addition, it minimizes the number of clusters and the number of nodes in the border area. As a result, it minimizes the broadcast overhead.
- *A Collaborative Learning Automate-based Channel Assignment*: A collaborative learning automate-based channel assignment named “CLACA-TP” (Kumar and Lee, 2015) has been proposed to maximize the effective transmission rate with minimum blocking probability and satisfy the topology preservation. The learn automate (LA) which located on each mesh router is used to choose an optimal action among the action set that maximizes the effective transmission rate with the minimum number of call block and channel switching. It takes the number of successful calls, traffic load of the currently used channel as the input. Then, it calculates the effective transmission rate based on this information for each channel. Once the mesh router received a request from mesh client it performs the LA. First, the LA checks the CUF and computes the channel condition based on the received information from the environment.
  In LA, the probability of action is computed based on the CUF

and effective utilization for each channel. Initially, every channel is assigned with the same priority value. The priority of each action in the action set is modified according to the channel quality. Based on the environment information, the LA computes the channel utility by computing the CUF and effective utilization. This value is used to determine the number of channels that satisfies the user's request. Each mesh router distributes this value to its neighbors. If the computed value is greater than the threshold, the current channel is rewarded. Otherwise, it decreases while increases the other channel probability. Besides, the proposed LA-based approach also maintain the topology preservation by constructing a priority queue from which channels are allocated to a certain link based on values of CUF and effective transmission rate. Each LA performs communication with its neighbors based on cost or request and number of received and departure request which is computed based on the entries of the priority queue.

- *Summary of Node Connectivity in Static Channel Assignment*: The static channel assignment assigns each interface of every WMN node to a channel with aims to minimize the total network interference and keep the node connectivity. Thus, some of the static channel assignment address the node connectivity and interference during the startup time. Their solution is to find an optimal solution that maximizes the node connectivity and minimizes the total network interference. They address the network connectivity issue either by proposing topology control or topology preservation channel assignment. The topology control refers to that each node is connected with k neighbor nodes that keeping the node connected with each node on the network (Mohsenian-Rad and Wong, 2007; Subramanian et al., 2007, 2006; Chaudhry et al., 2012; Devare, 2014; Tang et al., 2005; Marina et al., 2010; Doraghinejad et al., 2014; Bao et al., 2014). Some of the surveyed topology control approaches formulated the problem as conflict graph problem with aims to reduce the interference and keep the network connected (Mohsenian-Rad and Wong, 2007; Chaudhry et al., 2012; Tang et al., 2005; Marina et al., 2010). However, such approaches may difficult to consider channel capacity while maintains the network connectivity. The other approaches view the topology control problem as a joint problem which combines the channel assignment with power control or with power control and routing problem (Chen et al., 2007). The joint approaches may maximize the network performance because it takes into account more input constraints. However, such approaches solved the joint channel and topology control sequentially which may not give the optimal solution. In Mohsenian-Rad and Wong (2007), Chen et al. (2007), Doraghinejad et al. (2014), the CA and topology control jointly address to find an optimal topology and CA that maximize the network throughput.

In the topology preservation approach, all links on the single channel wireless mesh network logical topology are preserved on the feasible channel assignment solution (Kumar and Lee, 2015; Cheng et al., 2012, 2013; Athota and Negi, 2015). In case of topology preserving, the routing protocols which are fully researched of the single channel routing protocols can be applied to the WMN without further modification. In general, the advantage of address the network connectivity during the channel assignment stage is that it can avoid the network partition and the links failure. However, Since most of them are centralized, they need a coordination operation in WMN. Table 2 compares them based on the inputs, objective of outputs, techniques used, sequential/jointly and constraints.

4.3. Routing-aware channel assignment

As shown in Section 2, the network topology of an MRMC-WMN is the main factor for making the routing decisions which are influenced by the CA decisions. Thus, the routing decision is also dependent on CA. Besides, the routing can balance the traffic load in the network, which is the main factor considered by the load-aware CA. To handle such a relationship between CA and routing, the CA and routing are solved jointly. So, they are combined in order to obtain an optimal network performance. In this section, we review the joint optimization of routing and channel assignment. We classify the joint channel assignment and routing protocol for MRMC-WMN into two main types: joint unicast routing and channel assignment (JURCA) and joint multicast routing and channel assignment (JMRCA).

4.3.1. Joint unicast routing and channel assignment approaches

In this subsection, we review the joint unicast routing and channel assignment approaches as follows.

- *Hyacinth-based Channel Assignment*: Raniwala and Chiueh (2005) proposed a distributed channel assignment called “Hyacinth” based on spanning tree topology, where the gateway is the root of the spanning tree and most of the traffic in the WMN is from/to the gateway. The protocol divides the channel assignment problem into two sub-problems: neighbor-to-interface binding and interface-to-channel binding. The neighbors-to-interface refers to which parent the node should join and the channel-to-interface refers to distributed the channels among the DOWN-NIC in such way that minimizes the interference. In neighbor-to-interface binding stage, the node's interfaces are classified as UP-NIC or DOWN-NIC. The UP-NIC uses to connect the node with its parent while the DOWN-NIC uses for the node's child.

  The channel assignment starts from the root of the tree. Each node is responsible for selecting channels to its DOWN-NIC interfaces and switching the UP-NIC interface to the channel as used by its parent's corresponding DOWN-NIC. Once the node received a gateway route discovery message, it switches the UP-NIC interface to the corresponding parent's DOWN-NIC and then selects new channels for its DOWN-NIC interfaces based on two-hop traffic load information. Periodically, each node measures its channel load and exchange this information with its two-hop neighbors.

  In the RB-CA (Kim and Suh, 2010), instead of using the hop metric to construct the spanning tree logical topology, rate-hop utilization metric is proposed to construct the spanning tree logical topology. The rate-hop metric can alert the single hop low rate link to 2-hop high rate links, see Fig. 11(b). The basic idea of RB-CA (Kim and Suh, 2010) is to construct the spanning tree WMN, where the gateway node is the root, based on a high quality metric such as EET (Draves et al., 2004). Then least used channel assignment is applied to assign the non-overlapping channels to each link on the constructed topology, see Fig. 11(c). Similar to the RB-CA, CoCA (Kim et al., 2011) constructs the spanning tree based on high quality metric, then it proposed rate balance algorithm to distribute the rate over multiple child interfaces assign with unique channel. Once the child selects its parent, it sends joint message toward the parent node. The parent node rearranges the data rate in decreasing order and distributes the rate over the interfaces in such the maximum network throughput increases.

  For example, Fig. 12(d) that a new node F joins node A via low-rate link $F-A$. Hence, the parent node A runs the balancing algorithm so that two high-rate links $A-B$ and $A-C$ are isolated from low-rate link $F-A$ via channels 1 and 2, see Fig. 12(e). However, the CoCA restricts most of the links that are available in single-channel networks, because it is based on the tree architecture.

  The main advantage of the Hyacinth-based algorithm is that it does not suffer from ripple effective problem. However, it needs

Table 2
Summary of Main Features of Connectivity-aware CA Approaches.

Protocol	Input	Technique used	Seq./jointly	Network connectivity	Consts.
CTA	1. CG 2. Intf 3. Chl	1. Tabu-search 2. Color merging algorithm	Jointly	*K*-conn.	1. *K*-conn 2. Intf 3. Chl
BFS-CA	1. MRCG 2. Intf 3. Chl 4. ExtIf	1. BFS algorithm	Jointly	Conn	Conn 1 2. Intf 3. Chl
RCBFS	1. MRCG; 2. Intf; 3. Chl; 4. ExtIf; 5. PC profile	1. BFS algorithm	Jointly	Conn	1. Conn 2. Intf 3. Chl
ARSCA	1. MRCG; 2. Intf; 3. Chl; 4. ExtIf	1. BFS algorithm	Jointly	Conn	1. Conn 2. Intf 3. Chl
CLICA	1. CG 2. Intf 3. Chl	Fixed-based polynomial greedy algorithm	Sequential	*K*-conn	1. *K*-Conn 2. Intf 3. Chl
INSTC	1. CG; 2. Intf; 3. Chl;	Polynomial greedy algorithm	Sequential	*K*-conn	1. *K*-conn 2. Intf 3. Chl
TiMesh	1. TLoad. 2. Intf. 3. Chl. 4. LDR.	1. Formulate TP, CA and routing problem as LMIP 2. ILT is used to solve the LMIP	Sequential	Conn	1. Conn 2. Intf 3. Chl
JCTR	1. CG 2. Intf 3. Chl 4. TLoad 5. PC	Jointly adjustment of CA, transmission power, and routing	Jointly	Conn	Conn
DPSOCA	1. Original topology 2. Intf 3. Chl	PDSO optimization	Jointly	TPresv	1. Tpresv 2. Intf 3. Chl
TICA	Two-hop channel information	"Select *x* less than *x*" topology control based on power control before CA.	Sequential	*k*-conn	1. *K*-conn 2. Intf 3. Chl
IGSO	1. Original topology 2. CG 3. Intf 4. Chl	Aggressive search algorithm (GSO)	Jointly	Conn 1.	Conn 2. Intf 3. Chl
ComTac	Original topology	Cluster-based channel assignment	Sequential	Conn	Conn
CBCA	Original logical topology	Cluster-based channel assignment	Sequential	TPresv	1. TPresv 2. Intf 3. Chl
CLACATP	TLoad; Number of successful calls	Collaborative learning automate	Jointly	TPresv	1. TPresv 2. BW 3. Capacity
MSTICA	UDG	Priority-based minimum spanning tree approach	Sequential	*K*-conn	1. *K*-conn 2. LC 3. Intf 4. Chl

a long period of time, 5 to 10 second as stated in Hyacinth to discover the channels associated with DOWN-NIC of its prospective parents.

- *Load-Aware Channel Assignment* (*LA-CA*): In the LA-CA (Raniwala et al., 2004), the channel load is computed based on sum of traffic load for each link using the channel. Since there is mutual dependency between the routing and the link load, the algorithm assumes that the traffic load for each link is known. Based on the initiate estimated traffic load, the algorithm distributes the channel as follows:
  - The links order descending based on their traffic load.
  - For each visited link, it greedily assigns channel that satisfied the channel capacity constraints.

  Since the LA-CA uses a greedy heuristic search algorithm to distribute the non-overlapping channels among nodes, it is easy to implement in the reality. Its main limitation is that, due to the using of a simple greedy heuristic, it may lead to sub-optimum solution.

- *Maxflow-based Centralized Channel Assignment* (*MCCA*): Unlike the existing works which assumed that the traffic profile is known to break the interdependency between the channel assignment and routing problems, the MCCA proposed pre-compute flow rate. The pre-computed flow rate aims to compute the number of links that need to group together and sharing a common channel. The number of links in each group must satisfy the capacity constraint, the traffic load on each group does not exceed its channel capacity, while the number of groups per

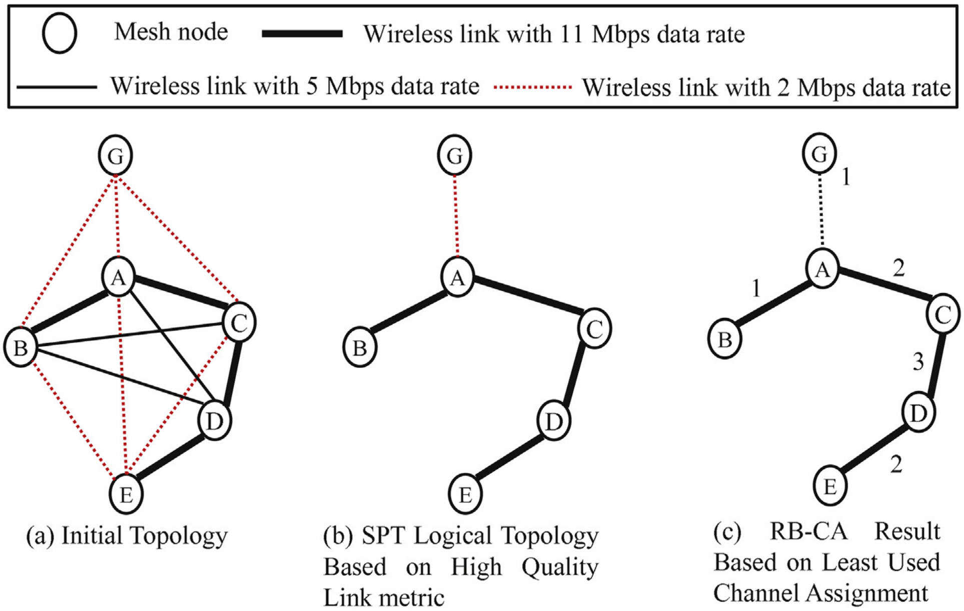

Fig. 11. An illustration for RB-CA channel assignment.

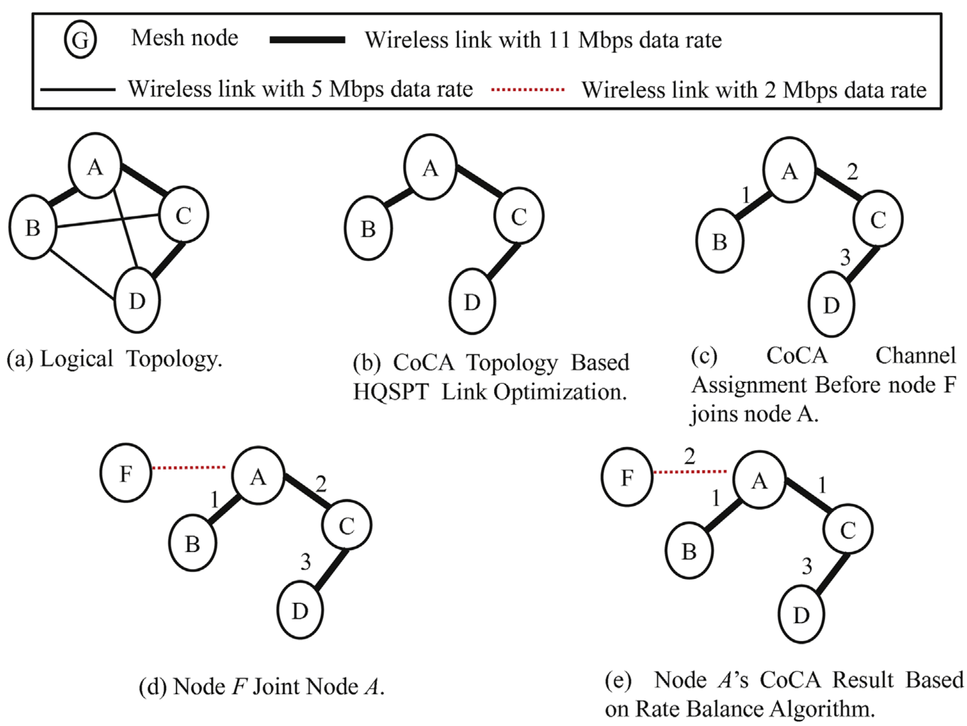

Fig. 12. An illustration for CoCA channel assignment.

a node must not exceed the number of radios on this node. Similar to Skalli et al. (2007), the MCCA starts by ordering the groups in descending order based on the maximum group utilization for each group. Hence, the group with high utilization is considered first and assigned with least interference channel. The major advantage of MCCA is that it achieves its first, second and fourth objectives for channel assignment by breaking the channel assignment problem into two stages. The main limitations of MCCA include: it may not achieve the maximum network throughput as mention in its third objective, since it used a simple ranking formula based on link load; and it does not consider the real traffic generated by the application layer.

- *Distributed Congestion-Aware Channel Assignment* (*DCACA*): In Mohsenian Rad and Wong (2009), the authors proposed a distributed congestion-aware channel assignment (DCACA) algorithm which executed by each node. The basic idea of DCACA is that each node monitors the traffic load of ingoing links. Once the node detects that one of its ongoing links becomes congested, it resolves the congested link by switching its corresponding interfaces for both link's nodes to the least load channel. In addition, the proposed algorithm improves the network capacity by utilizing both overlapping and non-overlapping channels. The protocol proposed mutual channel interference index which models the overlapping interference among channels. The algorithm reduces the complexity of congestion-aware channel assignment and efficiently utilizes the spectrum by utilizing both overlapping and non-overlapping channels. However, its overhead in term of switching overhead and the channel synchronization messages may increase, especially, when the traffic load increases.

- *Cluster-based Joint Channel Assignment and Routing Protocol*: In Mettali Gammar and Ghannay (2015), a cluster based joint channel assignment and routing protocol named "JRCAP" is proposed to minimize the total network interference. The protocols divided the network into balance clusters and then perform inter-cluster and intra-cluster channel assignment. The density-based cluster algorithm (Mitton et al., 2005) is used to divide the WMN nodes into clusters based on the density computation, which is the ratio between the number of links in the node communication range and the number of links in its interference range.

  The inter-cluster CA aims to minimize the total network interference by assign the neighbors clusters to different fixed channels. The central node is used to distribute the channels among the clusters through the graph coloring algorithms. Then, the central node broadcast the clusters and their fixed node to all nodes in the network. When the node receives the configuration message, it switching one of its interfaces to the corresponding channel allocated to the cluster. The remaining interfaces are assigned during the on-demand routing discovery. The channel selection is integrated with on-demand routing protocol with aims to maximize the channel diversity. Besides, the approach developed a new metric to address the channel diversity and link capacity. The metric developed based on the maximum residual capacity that takes into account the channel diversity, channel load, and link data rate. The main advantage of the JRCAP is that it can provide a better performance for application in term of ensuring minimum end-to-end delay and minimizing the number of packet loss. However, the approach does not take into account the mesh client which may impose performance reduction of the proposed scheme.
- *Robust Channel Assignment and Routing with Time Partitioning*: In Wellons and Xue (2014), a robust channel assignment and routing with time partitioning (RCART) was proposed to optimize the network performance under high traffic variation. The proposed algorithm consists of three stages. In the first stage, the interval time of channel reassignment is computed. To achieve this goal the daytime is divided into interval based on the traffic characteristic in the network. By given a real traffic load profile, the algorithm computes the interval where reassign channels among the links will lead to higher throughput. Then, at each interval time, the algorithm performs the robust routing algorithm and channel assignment stages. In the robust routing stage, the algorithm constructs the routing scheme that providing the upper worse case boundary of current network performance. The routing problem is formulated as an LP problem. In the channel assignment stage, the Simulated Annealing (SA) is used to distribute channels among the links with aims to balance the traffic load among the available channels. The worst-case congestion ratio is used as path and channel selection metric. This metric is used to compare the current routing's performance with the optimal performance. It is defined as the ratio between the performance of all possible demands and the optimal worst-case solution. The main advantage of RCART is that it achieves very close results to the optimal solution without incurring too much overhead as shown by the authors. However, since the RCART depends on known traffic profile, its performance is influenced by the used traffic estimation model.
- *Joint QoS Routing and Channel Assignment*: In Bakhshi et al. (2011), a joint routing and channel assignment named Joint QoS Routing and Channel Assignment (JQRCA) has been proposed to maintain the feasibility of path based on path throughput and capacity. The proposed protocol consists of routing algorithm which aims to find a set of k-hop paths and on-demand channel (re)assignment that maintains the established path adapted to the network behavior and feasible.

  Given a set of flows using path p to get to their destination, the JQRCA which located at the central node, periodically, checks the feasibility of the established path. If the path is not feasible which means does not satisfy the capacity constraint, the JQRCA tries to find the congested links and resolve the problem by assigning the links with new feasible channels. In case, there is no any feasible channel, the JQRCA performs a group change strategy. In the group strategy, the JQRCA aims to find the minimum set of links that can resolve the violate links by switching their channels.

  The main advantage of the proposed algorithm is that it can provide the upper bounds on the network performance. However, the WMN characterizes by a large number of multi-link and multi-path which may lead to a complicated path selection process with path feasible constraints. In addition, the JQRCA unawares of the adjacent interference which in turn may influence the network performance in a high-density network.
- *Joint Routing, Channel Assignment and Rate allocation* (*JRCAR*): The authorsof GAlvez and Ruiz (2013), proposed a joint routing, channel assignment and link rate allocation channel assignment scheme to balance the instantaneous traffic in WMN in such way that maximizing the network throughput and satisfied the proportional fairness among the flows. By given a set of flows at a t period of time, the JRCAR aims to optimize the throughput and fairness of the currently active flows by finding the best combination of channel route selection, channel selection, and rate allocation that satisfied the throughput and fairness constraints. To achieve the above objectives, the algorithm decoupled the routing, channel assignment and rate balance into three stages: routing, channel assignment and rate allocation (RA). The routing problem is solved first to balance the traffic for the input flows and avoiding the congestion. Then, the channel assignment and link rate are solved based on these routes. Hence, jointly routing, CA and link rate are solved sequentially. In the routing stage, the JRCAR uses the Dijkstra's algorithm to compute the multiple paths from the flow's source node to the destination. The algorithm, then, selects a path with minimum bottleneck is selected as the best. The next stage is the channel assignment which aims to improve the current channel assignment through several link-channel reassignment without violating the throughput and fairness constraints. The algorithm starts by sorting the links according to their load and attempt to reassign their channel. The number of allowed reassignment links depends on the readjustment threshold. The algorithm finishes when the number of reassign links exceeds the readjustment threshold. Finally, the proposed protocol dynamically allocates rate for each flow based on channel traffic load.

  The main advantages of this algorithm are: First, it is first protocol that jointly routing, CA and rate allocation problems with an intended adaptation period less than 60 s. Second, since the algorithm sequentially solving the jointly routing, CA and RA problems, it has low complexity and small overhead. Third, due to the minimum assumption of the capacity model, the algorithm is suitable for real implemented. However, its limitations are: First, due to the need of centralized coordination, the algorithm suffers from single node failure. Second, since the algorithm adopts heuristic algorithm to solve the CA, there is no guarantee for its worst case. Third, since the algorithm adapted to the frequently traffic changes, it may limit the network performance because of frequent interface switching overhead.

- *Link Scheduling, Rate Allocation, Routing and Channel Assignment*: In Glvez and Ruiz (2015), the authors demonstrated that link scheduling, rate allocation (LRA), routing and Channel Assignment (CA) are dependent on each other, and the optimum result of each factor depends on the results of the other factors. Thus, in order to fully utilize network spectrum resources, the authors proposed a joint channel assignment, routing and rate allocation named "JML" based on the known traffic profile for multi-rate WMN. The JML consists of three stages – On purge, Search interference range, routing and channel assignment. On purge stage, the JML optimizes the original topology by removing the unwanted links from logical topology based on traffic know profile method. The basicidea of the purge stage is that the yen algorithm (Yen, 1970) is used to compute the *k*-shortest paths between the gateway and every node in the WMN. The links that are not included in any of computed paths are removed from the logical topology. On the SINR stage, Search interference range algorithm (SIR) is proposed to find the interference range for each link. The basic idea of SIR is to find the link's interference range that maximizes the network capacity. Then, it assigns the highest rate for each link in such a way that the link's interference range does not exceed the desired range. Finally, the JML solves the routing and channel assignment as MINPL problem based on the link rate allocation information computed in SINR stage.
- *On-demand-Based Channel Assignment*: The on-demand based channel assignment algorithms follow an on-demand style in channel assignment. During the Routing REQuest message (*RREQ*), each node selects a channel for the current established path and when it received a Routing REPly message (*RREP*), it switches an interface to the selected channel. The channel negotiation performs through a common channel. The AODV-CA (Gong et al., 2009) proposed for dynamic interface switching where a channel is assigned to interface based on the received flow. Moreover, the AODV-CA selects a node's recommended channel based on the least used channel. In the JCAR (Chiu et al., 2009), the dynamic interfaces are classified as receiving and sending in order to utilize the multi-interface at intersection nodes where multiple flows are received by the node. The JCAR selects a channel based on least load channel interference index. In CA-LQSR (Yuan et al., 2012), the scheme uses the calculated transmission time as channel interference metric for channel selection. The M-AODV-M (Zhou et al., 2012), proposed joint routing and channel assignment to address the channel reuse problem along the established path. However, most of these algorithms proposed for ad hoc network and may not efficiently utilize the WMN characteristics to reduce the channel assignment complexity. Moreover, integrating channel assignment with reactive routing discovery process will increase the packet end-to-end delay. The proposed methods differ in the way of channel selection and utilizing the multi-radio interfaces per mesh router to keep the network connectivity and increase the node capacity.
- *Summary of Joint Unicast Routing and Channel Assignment Approaches*: A joint unicast routing and CA can be classified into off-line and on-line channel assignment according to the input parameters. The off-line joint CA and routing assumed that the traffic profile is given as input to the channel assignment and their objective is to maximize the WMN capacity and throughput (Raniwala et al., 2004; Wellons and Xue, 2014; Glvez and Ruiz, 2015). So, they usually produce optimal results than the on-line approach. However, this approach cannot be adapted well for a dynamic network. In addition, it needs network updated and significant overhead. To adapt the off-line approach to work well with the traffic changes, the authors in Wellons and Xue (2014) developed a centralized joint channel assignment and routing based on the idea of daytime partition. In this approach, the channel and routing are recalculated according to a set of predetermined time interval that lead to maximize the network capacity. Besides, the off-line approach formulated the problem as MPI optimization problem (Glvez and Ruiz, 2015; Wellons and Xue, 2014) and developed a heuristic approaches to solving the problem. However, this approach assumes that the global information such as traffic profile is given as input to the algorithm.
  On the other hand, the on-line approach has been developed to adapt to traffic change by ensuring path stability constraint (Raniwala and Chiueh, 2005; Chiu et al., 2009; Gong et al., 2009; Yuan et al., 2012; Zhou et al., 2012; Mettali Gammar and Ghannay, 2015) or avoiding link congestion (Mohsenian Rad and Wong, 2009; Bakhshi et al., 2011). Such approaches utilize the routing information to predict the channel condition. Once they discover the link is congested along the established paths, they perform channel (re) assignment. Some of the on-line approaches used the routing information to recalculate the channel assignment. Such approaches aim to maximize the network capacity and system throughput. However, recalculating the channel assignment for whole links on the network leads to high interface switching which in turn affect the throughput and packet end-to-end delay. Therefore, most of the adapted channel assignment approaches limit the number of readjustment links according to the readjustment threshold. Some of the on-line approaches integrated the channel assignment with the on-demand routing discovery process (Chiu et al., 2009; Gong et al., 2009; Yuan et al., 2012; Zhou et al., 2012). However, their switching overhead depends on the link and path stability. Therefore, in a high-density network, they will suffer from high interface switching. In general, the on-line approaches made their decision based on the local information which may not find a near-optimal channel assignment. A comparison of joint unicast routing and CA is given in Table 3.

4.4. Joint multicast routing and channel assignment

In this section, we review the joint multicast and CA that solve the multicast routing and channel assignment jointly.

- *Utility-based Channel Assignment*: In Kumar et al. (2013), a utility-based channel assignment named "UBMR-CA" is proposed to address the multicast routing and CA takes into account the variability of the traffic demand from the end user. The scheme takes the mobile clients, mesh routers and gateways as inputs and constructs a multicast tree based on the link utility. The link utility can be computed based on the combination of its load, capacity, and interference. These values are computed over the time and the channel assignment is performed based on these computed values. The UBMR-CA consists of two stages: construction of utility-based multicast tree and channel assignment. In the first stage, the multicast tree is constructed by computed the utility value for each link and the links are grouped based on 2-hops distance. In the second phase, the flow demands are mapped among the available channels based on the link utility. The UBMR-CA, first, computes the utility weight metric (UWM) for each link based on the link capacity, load and interference with *k*-hop neighbors. Then, once the link's UWM is computed, a unique channel, that satisfy the capacity, bandwidth and interference constraints, is assigned to each individual link based on the link utility. However, the main drawback of this approach is the computational time and overhead caused by periodically computing link utility for

Table 3
Summary of main features of unicast routing-aware CA approaches.

Protocol	Input	Tech. Used	Switching Overhead	RJThr	Seq/Jointly	Consts
LA-CA	1. CG 2. Original topology 3. Chl	Fixed-base polynomial greedy CA algorithm	Medium	No	Jointly	Intf; Chl
Hyncain	Two-hop traffic information	On-demand channel assignment	Medium	No	Jointly	No
MCCA	1. FlowR 2. Intf 3. Chl	1. Formulated CA as link-group and group-channel 2. Polynomial Greedy CA algorithm	NO	NO	Seq.	intf; Chl
JRCAP	1. Logical topology	1. Graph coloring algorithm 2. on-demand cluster-based CA algorithm	High	NO	Jointly	intf; Chl
DCACA	Two-hop traffic information	1. Channel select based on mutual interference matrices 2. Switching a high congested link to least load channel	Low	NO	Seq	Capacity; Intf;Chl
JRCAR	1. Current TLoad 2. Logical topology 3. Intf 4. Chl	1. Heuristic algorithm to solve routing and CA. 2. Solve NLP convex optimization problem for RA	Medium	Time threshold	Jointly	Intf; Chl; ChlRJ
RCART	1. Day traffic profile 2. Intf 3. Chl	1. Formulated the routing problem as LIP problem 2. SA to optimize channel assignment	Low	CA Recalculated	Seq	Intf; Cong; Capacity
JQRCA	1. A set of flows using path *p*	1. MINPL to solve routing 2. Heuristic algorithm to solve CA	Low	A set of links	Jointly	intf; Chl; Capacity
JMR	1. Multirate traffic profile 2. Intf 3. Chl	MINPL to solve routing and CA	No	No	Jointly	intf
JCAR	Two-hop traffic information	Integrated reactive routing protocol with interference-aware CA	High	No	Jointly	No
AODVCA	Two-hop channel information	integrated reactive routing protocol with interferenceaware CA.	High	No	Jointly	No
AODVMRCR	1. Path channel information	Cross-layer interference-aware gateway reactive CA 2. Logical topology	Low	Time expired	Jointly	No
MAODVM	Two channel	Information, integrated reactive routing discovery process with interference-aware CA	High	No	Jointly	No

each link.

- *Distributed Polynomial-time Priority-aware Channel Assignment*: In Lin and Zhuang (2013), a polynomial time and heuristic distributed priority-aware channel assignment called "NOPA" has been proposed to solve the joint multicast routing and CA problem in WMN. The main objective is to minimize the impact of a new multicast request on the existing multicast tree based on the priority consideration. Whenever a new request is received, a multicast tree is constructed and channels are assigned to every node based on the node delay constraint. Hence, a channel that satisfies the node delay constraint and minimizes the total network interference will be selected as the best node's channel.
  The main idea of the distributed NOPA is that the path delay constraint is distributed among the nodes in the new multicast tree and then it performs node-based channel selection based on the node delay constraint. Therefore, the first step of NOPA is to divide the path delay among path's nodes by performing post-order and level-order to compute the delivery response from the children to the root of the tree and from the root to the leaf of the constructed multicast tree. Once the node-based delay constraint from each node in the multicast tree is computed, a node performs channel assignment. First, it computes the channel interference level for each channel. Then, the channels are sorted into a descending order based on their inter-tree interference. Finally, the best channel that satisfies the node delay constraint and minimizes the total network interface will be selected as a node's recommended channel. However, since the NOPA computes the channel assignment sequentially, it may produce a suboptimal solution.
- *I-QCA*: In the above studies, the channel assignment and the multicast routing problems are solved sequential and follow heuristic or meta-heuristic approaches which are not so fruitful because of their convergence towards local optima. In Chakraborty (2015), the authors proposed an I-QCA algorithm to overcome such problem by solving both the multicast routing and channel allocation conjointly based on genetic algorithm. The aim of the scheme is to find a multicast tree with minimum bound interference and the lowest multicast tree. To achieve the above objective, the I-QCA takes the multicast information, such as sender and its a set of receivers with jitter and delay bound, as input and computes the minimum interference multicast tree that satisfies the path delay and jitter constraints. Given the link *r* on the multicast tree, the I-QCA ensures that the average link delay and jitter for each link along the established path from the receiver up to the link *r* should less than the link's delay and jitter thresholds. The GA algorithm generates an optimal channel assignment solution from initial solution. A heuristic

algorithm was proposed to assign the non-overlapping channels among the links. Then, the GA is applied to optimize the current solution. In the next step, the GA is applied with the differential evolution approach to construct a multicast tree that satisfied the delay and jitter constraints. The main advantage of I-QCA is that its first protocol address both CA and multicast routing jointly based on intelligent computational method. However, its main limitation is that the joint technique is less suitable as it tightly coupling and maintains modularity.

- *Cross-Layered and Load-Oriented Multicast Routing and Channel Assignment*: In Yang and Hong (2014), a heuristic cross-layered and load-oriented multicast routing and channel assignment approach named "CLLO" has been proposed to find an interference-free multicast tree that maximizes the number of users serviced by the sender and satisfied the delay constraint. Given the directed graph G, gateway, and set of receivers, the CLLO computes the node's weight value for each node in the directed graph. This procedure starts by assigning each node in the direct graph with a level value computed by breadth first traversal procedure. Then, the weight value of each link is computed according to the number of mesh clients serviced by the node. The procedure is carried out in a down-top manner. After constructing the weight graph, a free-interference multicast tree is constructed in a top-down fashion. Initially, the CLLO starts with a partial multicast tree T, including only the gateway node. Then, a feasible link l that connects a node a, where $a \in T$, with b, where $b \notin T$, is added to the partial multicast tree. In case there no feasible link is found, the CLLO performs channel adjustment procedure which refers to change the channel allocation to the links until there is at least one feasible link is found. This procedure is repeated until there is no feasible link can be allocated with an interference-free channel.
- *Multi-objective Genetic Approach*: In Vaezpour and Dehghan (2013), a multi-objective genetic approach named "NSGA-II" has been proposed to find a multicast tree with low cost, low delay and low interference in WMN. The NSGA-II formulated the joint multicast routing and CA as a multi-objective optimization problem. In NSGA, an enhancement NSGA-II algorithm (Skalli et al., 2007) is used to solve the multi-objective optimization problem of joint multicast route protocol and channel assignment. During the iteration of NSGA, the approach constructs a multicast tree where the constructed tree must work better on at least one objective value than the others solution. Finally, the NSGA generated the final multicast tree from those sub-solution multicast trees which cannot be improved with the respect to any objective.
- *Level-based Channel Assignment*: In Zeng et al. (2010) and Lim et al. (2011), level based channel assignment named "LCA" and "MMCA", respectively, have been proposed to enhance the throughput of multi-radio multicast wireless mesh network. The basic steps of the level based channel assignment are that, first; it obtains the level value of each node in the WMN based on the BFS algorithm. Second, a multicast tree is constructed based on the node level information. Initially, the sender and its multicast receivers are attached to the tree. Then, for each receiver, its parent is needed to be found. If there is one of its parents on the tree, then the node is connected with this parent. Otherwise, it randomly chooses one of its parents. This step is repeated until all receivers are visited and connected with the tree.

  Next, the nodes are grouped according to their level information and assigned with a common channel. Assume the gateway is the source node and nodes a,b, and c are the multicast receivers. At the beginning, the tree contains only the gateway and the receivers. Starting from random choose receiver, the algorithm chooses its parent. This process is repeated until all receivers are added to the tree. Fig. 13 shows the grouping of the node according to their level information. We can observe that the gateway at level zero, nodes a,b at level one, nodes c,d,e at level two and h,j at level three, and each level is assigned with a unique channel.

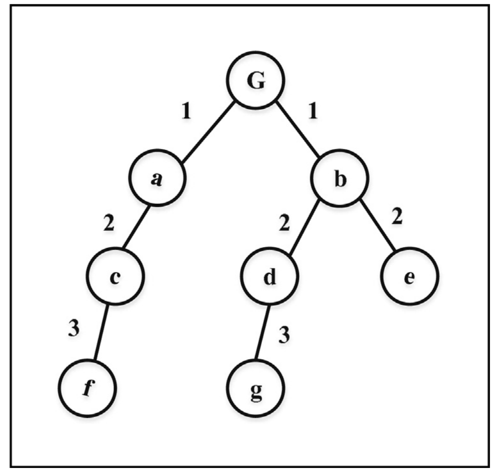

Fig. 13. LCA channel assignment.

  The main advantage of LCA and MMCA is that it's very simple to be implemented and it can improve the throughput. However, its main drawback is that it does not consider the interference generated at the same level. To overcome the interference caused by same level, the authors in Zeng et al. (2010) proposed Ascending Channel Assignment (ACA). The basic idea is to remove the link that connected the two nodes at the same level from the constructed tree. The ACA is enhanced by MCM heuristic channel assignment to utilize all available channels of a WMN, not just non-overlapping channels. By utilizing both overlapping and non-overlapping channels, the MCM can achieve the minimum node interference for its neighboring nodes. However, this Level based channel assignment cannot restrict the amount of the interference incurred by each path of the multicast tree. This may result in an unfair transmission delay distribution among the paths of multicast trees. The transmission delays of certain paths may be larger than the required path delay constraint. Furthermore, the MCM algorithm does not discuss the interference between multicast trees.
- *Quality of Services Multicast Routing Channel Assignment*: Authors in Cheng and Yang (2011) proposed quality of services multicast routing channel assignment named QoS-MRCA to find low cost and minimum-interference multicast tree that satisfied the end-to-end delay. By given a set of mesh nodes, gateway, a set of receivers, and the upper delay-bound constraint, the QoS-MRCA tries to find delay-bounded multicast tree. For each link in the delay-bound multicast tree, the QoS-MRCA allocates a channel to the link. The selected channel should have a minimum channel conflict among the available non-overlapping channel and it should satisfy the delay-bound constraint. The channel conflict is defined as the total number of interfering links with the link's interference range. Three evolutionary approaches, genetic, simulated anneal and tabu-search, have been proposed to solve the problem, separately.

  These approaches, iteratively, modified the initial population according to the fitness function. On the other words, the algorithms try to find the optimum solution by altering the route from source node to a multicast receiver and channels assigned to the links along the path. The initial population for all these approaches is computed by the LCA and shortest path algorithm while the fitness function is defined as the channel conflict. In QoS-MRCA, all outgoing links from the node are assigned with a same channel according to WMA (Niranjan and Pandey, 2006). However, the interference still exists between the nodes at the same level in the multicast tree. Moreover, due to WMA and ascending CA, not all available non-overlapping channels can be utilized when the number of levels is smaller than the number of non-overlapping channels.

- *Learning Automata Multi-casting Routing algorithm*: In learning automata approach, each node enhances its selected channel to the optimum channel by continuous repeated interactive with *k*-hop neighbors. In this regard, each node makes a decision about selected channel and responds to the selected neighbors channel. In Pediaditaki et al. (2009), the authors proposed distributed Probabilistic Channel Set Adaptation Channel Assignment (PCSA-CA) to overcome the PCA?s problems, switching overhead and channel assignment. To achieve the first objective, the authors proposed a novel neighbors discovery process which can describe as follows. For any two nodes share a common channel, their control messages are sent over this channel. In case the neighbor nodes do not share a common channel, the algorithm used the access channel -channel for connected client with the access point- to sent the control message as well as the data over all unused channels. To solve the second problem, channel assignment problem, the authors proposed a novel probabilistic channel set adaptation algorithm used at each node for channel assignment based on the learning automata approach. The algorithm uses the learning algorithm to choose the best channel for each radio according to the channel usage in its neighborhood. Initially, each node randomly selects a channel from the non-overlapping channel. After that, it evaluates the channel quality based on the channel probability. The channel probability is increased or decreased based on the quality of the current channel among the remains channels. If the quality of the current channel is the best among all non-overlapping channels, the probability of the current channel increasing, otherwise decreasing while the probabilities of remaining channels are increased. However, since the proposed algorithm in Pediaditaki et al. (2009) proposed for unicast-based network, the algorithm is not scalable and may not work well for the multicasting network (Jahanshahi et al., 2013). Moreover, the algorithm independently solves the channel assignment from the multicasting protocol. Hence, the authors in Cheng and Yang (2011), Jahanshahi et al. (2013) proposed Learning Automata Multi-casting Routing algorithm (LAMR) to solve the channel assignment and multi-casting routing protocol conjointly. The algorithm consists of two stages. On the first stage, the multi-casting source and destination topology is constructed based on the minimum end-to-end delay from each multi-casting source nodes to every multi-casting destination. In the second stage, the learning automata algorithm is applied to the constructing tree to achieve minimum interference tree as discussed above. Accordingly, the limitations of the learning automata-based algorithms mainly include it needs more time to find a feasible channel assignment when the traffic pattern in the network changes and it does not consider the impact of the client nodes on network performance.
- *Summary of Joint Multicast Routing with Channel Assignment*: In this section, we introduce the joint multicast routing and channel assignment approach. The joint multicast routing and CA problem is solved either sequential, where the multicast tree is constructed first and followed by the channel assignment, or jointly, where both multicast routing and CA are solved jointly. In the first category, the CA depends on the result of the first stage, constructed multicast tree. Hence, find a proper multicast routing metric yields to a simpler CA that efficiently utilizes the channel resources and maximizes the network throughput. The MCM (Lim et al., 2011), LCA (Lim et al., 2011) and MMCA (Zeng et al., 2010) proposed a minimum number of relays and hop count to construct the multicast tree. However, it suffers from the hidden node problem. In UBMR-CA (Kumar et al., 2013), the multicast tree and channel assignment are computed based on the sum of the link weight utility along the path. This metric is computed based on link load, capacity. In NOPA (Lin and Zhuang, 2013), the minimum cost tree in term of path delay is used to construct the multicast tree for the received request. However, the main drawback of the sequential approach is that only sub-optimum solution can be found and it may not work well with the determined multicast tree.

  For the second category, both channel assignment and multicast routing are solved jointly. Most of jointly approaches utilized the evolutionary optimization methods such as tabu-search (Jahanshahi et al., 2013; Cheng and Yang, 2011), simulated anneal (Cheng and Yang, 2011) and genetic algorithm (Chakraborty, 2015; Vaezpour and Dehghan, 2013; Cheng and Yang, 2011). Their solutions depend on the initial solution and fitness function which is used to compute channel-allocation multicast tree. However, minimizing the computational cost of the evolutionary methods while obtained a nearly optimal solution can be considered as the main challenges of evolutionary optimization assignment and routing approach. A comparison of joint multicast routing and CA is given in Table 4.

5. Summary to all CA approaches

In the previous subsections, we have surveyed state-of-the-art channel assignment approaches, with their advantages and limitations. As an overall summary of these approaches, we use the following classification keys to compare and contrast them:

1. Technique used to solve the channel assignment (Tech).
2. *Link optimization*: Defines if the problem is formulated such that minimizes the number of edges in the conflict graph before distributed the channel among the links. As the discussion on Section 3, we have five types of link optimization, spanning tree (SPT), flow-based (FB), known traffic profile(KnTr), power control(PC) and high quality metric(HQM).
3. *Node connectivity*: Defines if the channel assignment keeps the network connected.
4. *Routing*: Define if the channel assignment addresses the routing design issue. As discussed above, the channel assignment can be combined with unicast or multicast routing
5. The physical model is used as the interference model (PhyM).
6. Fault tolerance is addressed (FaTo).
7. Quality of service is supported (QoS).
8. *Overlapping channel resources* (*OCHL*): In addition to the CA can utilize the non-overlapping channel, this key refers to whether the CA also utilizes the overlapping channels resources or not.
9. *Client related issues*: Refers to that if the channel assignment addresses the mesh client issues, such as mobile handoff, traffic load and energy, during the channel assignment design stage.

Table 5 shows the comparison of channel assignment approaches based on techniques used to solve the problem and the above classification keys. For property 1, Table 5 shows that the channel assignment can be classified into four categories -on-demand (OnD), Gateway-oriented (GTWO), graph-based, evolutionary optimization approaches and others. The on-demand and gateway-oriented channel assignment used a single common channel (Raniwala and Chiueh, 2005; Kim and Suh, 2010; Kim et al., 2011; Chiu et al., 2009; Gong et al., 2009) or multiple

Table 4
Summary of main features of multicast routing-aware CA approaches.

Protocol	Input	Tech. used	Objective	Seq./jointly	Tree construction metric	Consts.
NOPA	1. Current multicast tree 2. New received multicast request 3. Number of channels	1. Polynomial heuristic priority-aware algorithm	Minimize the interferences for all existing multicast tree while satisfied the node-based delay for the new request	Sequential	N/A	1. Chl 2. Node delay
UBMRCA	1. Number of mesh clients 2. Number of mesh routers 3. Number of gateways	Heuristic utility-based CA based on conflict graph	Minimize the path utility from the source node to destination	Sequential	Path with minimum utility	1. Capacity 2. BW 3. Intf
I-QCA	Source node and its receivers with delay and jitter bound	Genetic method	Find minimal interference low cost multicast tree that satisfied delay and jitter constraints	Jointly	minimum interference and tree cost	Path delay and jitter
CLLO	1. Number of mesh clients with each mesh router 2. Number of mesh routers 3. set of multicast	Heuristic utility-based CA based on conflict graph	Minimize the path utility from the source node to destination over the time	Jointly	Number of serviced mesh client	Path delay
NSGAII	1. Source node 2. Set of receivers	Non-dominated sorting genetic method	Find low delay, low cost and low interference multicast tree	Jointly	Tree cost	End-to-end delay
LCA	1. Source node	1. Level-based channel assignment 2. Set of receivers	Improve the throughput of multicast networks 2. Ascending channel assignment	Sequential	Minimize intra-flow	No
MMCA	1. Source node 2. Set of receivers		1.Improve the throughput of multicast networks 2. Utilize both overlapping and non-overlapping channels	Sequential	Minimum interference	1. Intf
QoSMRCA	1. Number of mesh routers 2. Number of multicast receivers 3. Upper delay-bound constraints	Three evolutionary methods, genetic, simulated anneal and tabu-search	Find low cost and minimuminterference that satisfied the upper delay-bound	Jointly	Low tree cost	Upper delay-bound
LARM	1. Source node 2. Set of receivers	Learning-based algorithm based on learning automata	Minimize the interferences for multicasting networks	Sequential	Minimal end-to-end delay	No

Table 5
Comparative study of the outstanding structures of channel assignment approaches.

Protocol	Tech. used	LinkOP					Connectivity						Routing		Client issues			FaTo	QoS	PhyM	OCHL
		SPT	KnTr	FB	PC	HQM	CCHL	MCHL	SW	*K*-conn	Conn	Presv	UNR	MCR	TL	Hf	Enrg				
CTA	COFG;TS	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	No
BFS-CA	COFG;BFS	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	No
ARSCA	COFG;BFS	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	No
RC-BFS	COFG;BFS	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	No
CLICA	UDG;HS	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	No
INSTC	UDG;HS	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	Yes	No	No
TiMesh	ILS	No	No	No	No	Yes	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No	No	No
JCTR	COFG;HS	No	No	No	Yes	Yes	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	No
DPSO-CA	PSO	No	No	No	No	No	No	No	No	No	No	Yes	Yes	No	No	No	No	No	No	No	No
IGSO	GSO	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No	No	No
TICA	CONNG;HS	No	No	No	Yes	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
ComTac	GTWO	No	No	No	No	No	No	Yes	No	No	No	No	Yes	No	No	No	No	No	No	No	No
CBCA	HS	No	No	No	No	No	No	No	No	No	No	Yes	Yes	No	No	No	No	No	No	No	Yes
MSIT-CA	UDG;HS	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No	No	No
CLACA-TP	LA	No	No	No	No	No	No	No	No	No	No	Yes	Yes	No	Yes	No	No	No	Yes	No	No
Hyacinth	GTWO	Yes	No	No	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
DCACA	No	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No	Yes	Yes
JRCAP	GCA;OnD	No	No	Yes	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	Yes	Yes	No
JRCAR	CONNG,HS	No	No	Yes	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	Yes	Yes	No
RCART	SA	No	Yes	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
JQRCA	MIPL	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	No
JML	MIPL	No	Yes	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No
LA-CA	Gready	No	No	No	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
MCCA	UDG;HS	No	No	No	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
AODV-MRCR	OnD	No	No	Yes	No	No	No	Yes	No	No	No	No	Yes	No	No	No	No	No	No	No	No
AODV-CSHDIA	OnD	No	No	Yes	No	No	No	Yes	No	No	No	No	Yes	No	No	No	No	No	No	No	No
AODV-CA	OnD	No	No	Yes	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
PCA	OnD	No	No	No	No	No	No	No	Yes	No	No	No	Yes	No	No	No	No	No	No	No	No
JCAR	OnD	No	No	Yes	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
CA-LQSR	OnD	No	No	No	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
RB-CA	GTWO	Yes	No	No	No	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
CoCA	GTWO	Yes	No	No	No	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
UBMR-CA	COFG;HS	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	Yes	No	No
NOPA	HS	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	Yes	No	No
I-QCA	GA	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	Yes	No	No
CLLO	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	Yes	No	No	No	Yes	Yes	Yes
LCA	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No
MCM	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes
LRAM	LA	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No
QoS-MRCA	LA,GA,SA	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	Yes	No	No
NSGA-II	GA	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No

common channels (Mogaibel et al., 2012; Naveed et al., 2007) for the network connectivity, which can support the fault tolerance. However, both of them do not address the mesh client issues, neither the fault tolerance in their design solution. Moreover, considering the instantaneous traffic enable the approach to avoid link congestion and adapt to traffic changes. Table 5 also shows that most of the proposed on-demand and gateway-oriented channel assignment integrated the channel assignment with unicast routing. Therefore, a multicast distributed on-demand based channel assignment becomes one of the future research directions.

In the second category, the channel assignment is carried out based on the graph theoretical model such as connectivity graph (CG), conflict graph (COFG) and unit disk graph (UDG). Table 5 shows that there are three approaches have been used to solve the graph-based channel assignment: graph coloring algorithm (GCA) (Subramanian et al., 2007; Chaudhry et al., 2012; Marina et al., 2010; Mettali Gammar and Ghannay, 2015), BFS (Subramanian et al., 2006; Devare, 2014; Revathi and Deva Priya, 2014) and graph partition (GP) (Sridhar et al., 2009). For the connectivity issues, some of these approaches addressed network connectivity during the channel assignment design stage while the others neglects the connectivity and assume there is a common channel used for the network connectivity. Moreover, the connectivity has been addressed by graph-based approaches by ensuring that the decision of the channel assignment should satisfy the *k*-connectivity or connectivity constraint. However, such approach may not support the fault tolerance since it does not grantee that there is always alternative path available when the old one is not available. Moreover, Table 5 shows that the graph-based CA has not been used to solve the topology preservation neither study the fault tolerance.

The third category is the evolutionary-based channel assignment where the optimum solution obtained from the initial solution. Table 5 shows the evolutionary-based methods has been used to solve joint channel assignment with unicast routing, multicast routing and connectivity. Moreover, it also shows that there are four types of evolutionary methods have been used to solve the channel assignment: PSO, genetic (GA), simulated anneal (SA), tabu-search (TA), and learn automata (LA). Other optimization techniques solve the problem mathematically through integral linear (ILP). However, their performance is limited by the computational time and storage required to compute the optimal solution. Furthermore, Table 5 shows that none of the evolutionary-based approaches has been applied to solve the congestion problem and adapted to traffic change.

For property link optimization, it efficiently utilizes the spectrum by reducing the number of links in the logical topology before applying the channel assignment. However, it needs some criteria to decide which link should be removed or omitted during the channel assignment. For example, the known traffic profile (KnTr) approaches construct the logical topology based on the traffic carried by each link and the link that has no traffic will be removed or omitted from the logical topology. The spanning tree (SPT) and high quality metric assume that the most of the traffic is toward the gateway. According to such assumption, the spanning tree approaches construct the logical topology based on the gateway paths from each node. However, in the high quality link optimization, a high quality metric, such as ETT, is used to construct the spanning tree topology instead of using hop count metric. Furthermore, the flow-based approach uses the reactive routing discovery messages for link optimization which implies that the CA is applied only to the links involve on the established path from the source to destination. There is a relationship between link optimization criteria, fault tolerance and network connectivity. The known traffic profiles and spanning tree link optimization channel assignment do not address the node connectivity neither the fault tolerance. This is because of their assumption regarding to the traffic load or traffic pattern. They assume the traffic is toward the gateway and infrequently changes. Hence, they use a common channel for network connectivity. The power control link optimization channel assignment removes undesired links from the logical topology; resulting in high quality logical topology which may suffer from the network partition and fault tolerance. Some of power control link optimization schemes addressed the topology preserving while minimizing the total network interferences (Chaudhry et al., 2012).

For the connectivity property, Table 5 shows also that all distributed algorithms do not address the topology preserving, some of them using the common channel (Raniwala and Chiueh, 2005; Skalli et al., 2007; Kim et al., 2011; Mohsenian Rad and Wong, 2009) while others using channel switching to keep the network connectivity (Pediaditaki et al., 2009; Kyasanur and Vaidya, 2006). Using a common channel in a high-density network may lead to channel congestion due to all nodes using the common channel for their control messages transmission. Moreover, the channel switching will increase the packet end-to-end delay as the environment is changed. Moreover, Table 5 also shows that the joint multicast routing and channel assignment neglects the network connectivity during their channel assignment design. In addition, most of the multicast approaches are centralized approach. Therefore, due to the lack of distributed joint channel assignment and multicast routing, a distributed joint solution is needed to be developed in order to overcome the limitation of centralized approach. Table 5 also shows that only limited researches of the current CA have been addressed the fault tolerance, mesh client issues and dynamic approach with SINR model. Accordingly, these three issues are further discussed in the next section about future research directions. Furthermore, Table 6 shows the joint approach for the CA based on the interference index, routing and connectivity.

6. Future research directions

In this section, we first foresee the general research directions for CA, and then point out some specific research directions. From Table 5, there are several issues that are worth further study in the dynamic channel assignment, such as how to coordinate the channel assignment of both static and dynamic interfaces, how to route the data toward the destination while aware of the channel assignment to achieve the best performance and how to determine the optimal number of interfaces on each interface group, static and dynamic. We can also conclude the future research issues for the centralized approach as follows. The centralized approach based on the known profile has not been jointly addressed the fault tolerance, routing and topology preserving and hence further study is required. Besides the above general directions, we also highlight the following specific issues, which are not fully addressed or remain unaddressed by the current CA approaches.

1. *Dynamic technique with physical model*: As shown in Table 5, most dynamic channel assignment approaches model the interferences based on the protocol model, which is not accurate enough to model the real network environment. We believe that it is necessary to model the dynamic channel assignment approaches based the physical model instead of using the protocol interference model.
2. *A new technique to model external interferences*: Since most WLAN networks are co-located with other wireless networks such as 802.16 operate in the unlicensed radio frequency bands, there is no guarantee that other external wireless sources do not use the same bands. Hence we believe that consider the external interference become more important in designing the CA approaches. In the above surveyed approaches, only BFS-CA (Subramanian et al., 2006) and ITA-CA (Riggio et al., 2011) consider the external interference. Unfortunately, it can only detect the interference from external wireless networks using the IEEE 802.11 standard, since its external interference monitoring relies on the identification of external MAC addresses. We believe that the basic means to address this issue is to exploit the rich functionalities provided by the physical layer to retrieve the channel status.
3. *Optimum readjustment threshold for adaptive channel assignment*: The basic idea of the adaptive channel assignment is to adapt to the traffic changes through successive link-to-channel reassignment that minimize the system throughput. However, one of the main issues of the adaptive channel assignment is the responsiveness of the system which depends on the frequent recalculated the channel assignment and the number of readjustment links. Hence, the key requirement design of adaptive channel assignment is the speed and efficiently. As results, an optimum threshold for the channel recalculated and number of links readjustment is needed to be developed.
4. *Issues related to mobile client*: The first issue is the mobile handoff; when a mesh client moves from one mesh router to others. This process involves the channel scanning, the channel association and the path re-route which may disrupt the real time traffic and increase the latency. This problem can be solved by maximizing the node connectivity with its neighbors. However, due to the tradeoff relation between the connectivity and interference, a proper joint channel assignment and routing protocol that minimize the handover overhead become an issue in multi-radio multi-channel WMN. Besides, with the mobility of mesh client, the traffic load at each mesh router become dynamically and cannot predict. Hence, the second issue is the traffic load generated by mesh client that needs to be forwarded on the network by mesh routers. By Considering the impact of handoff on the traffic load and the total traffic load carried by mesh routers, researchers in channel assignment need to develop a new load-aware channel assignment taking into account the traffic changing caused by mesh client handoff.
5. *Joint channel assignment and routing for hybrid traffic*: Joint channel assignment and routing approaches are mainly developed for unicast or single flow multicast, where there is a single source node and multiple receivers. In WMN, there are multiple unicast and multicast flows with different source and destination nodes. Therefore, the interference caused by the multiple unicast flows, multiple multicast flows and the between the unicast and multicast need to be investigated.

Table 6
Comparison of different CA based on our channel assignment classification.

Protocol	Interference							Connectivity	Routing
	Metric used	IntraF	InterF	EXIF	HD	Traffic	Link Rate		
CTA	Interference-aware	No	Yes	No	No	No	No	Yes	No
BFS-CA	Interference-aware	No	Yes	Yes	No	No	No	Yes	No
ARSCA	Interference-aware	No	Yes	Yes	No	No	No	Yes	No
RC-BFS	Interference-aware	No	Yes	Yes	No	No	No	Yes	No
CLICA	Interference-aware	No	Yes	No	No	No	No	Yes	No
INSTC	Traffic-aware	No	Yes	No	No	Yes	No	Yes	No
TiMesh	Traffic-aware	No	Yes	No	No	Yes	No	Yes	No
JCTR	Airtime metric	Yes	Yes	No	No	Yes	No	Yes	Yes
DPSO-CA	Interference-aware	No	Yes	No	No	No	No	Yes	No
IGSO	Interference-aware	No	Yes	No	No	No	No	Yes	No
TICA	Interference-aware	No	Yes	No	No	No	No	Yes	Yes
ComTac	Interference-aware	Yes	Yes	No	No	No	No	Yes	No
CBCA	Interference-aware	Yes	Yes	No	No	No	No	Yes	No
MSIT-CA	Interference-aware	No	Yes	No	No	No	No	Yes	No
CLACA-TP	Channel utility	No	Yes	No	No	Yes	No	Yes	No
Hyacinth	Traffic-aware	Yes	Yes	No	No	Yes	No	No	Yes
DCACA	Traffic-aware	No	Yes	No	No	Yes	No	No	Yes
JRCAP	Maximum residual capacity	Yes	Yes	No	No	Yes	No	Yes	Yes
RCART	Worse-case congestion ratio	No	Yes	No	No	Yes	No	No	Yes
JQRCA	Congestion-aware	No	Yes	No	No	Yes	No	Yes	Yes
JRCAR	Throughput-aware	No	Yes	No	No	Yes	No	No	Yes
JML	Throughput-aware	No	Yes	No	No	Yes	Yes	No	Yes
LA-CA	Traffic-aware	No	Yes	No	No	Yes	No	No	Yes
MCCA	Congestion-aware	No	Yes	No	No	Yes	No	No	Yes
AODV-MRCR	Interference-aware	Yes	Yes	No	No	No	No	Yes	Yes
AODV-CSHDIA	Interference-aware	Yes	Yes	No	Yes	No	No	No	Yes
AODV-CA	Traffic-aware	Yes	Yes	No	No	No	No	No	Yes
PCA	Traffic-aware	No	Yes	No	No	No	No	No	No
JCAR	Traffic-aware	Yes	Yes	No	No	Yes	No	No	Yes
CA-LQSR	Interference-aware	Yes	Yes	No	No	Yes	No	No	Yes
RB-CA	Traffic-aware	Yes	Yes	No	No	No	Yes	No	Yes
CoCA	Traffic-aware	Yes	Yes	No	No	No	Yes	No	Yes
UBMR-CA	Utility weight metric	No	Yes	No	No	Yes	No	No	Yes
NOPA	Node delay	No	Yes	No	No	Yes	No	No	Yes
I-QCA	Path and jitter delay	No	Yes	No	No	Yes	No	No	Yes
CLLO	Interference-aware	No	Yes	No	No	Yes	No	No	Yes
LCA	Interference-aware	Yes	Yes	No	No	No	No	No	Yes
MCM	Interference-aware	Yes	Yes	No	No	No	No	No	Yes
LRAM	Interference-aware	No	Yes	No	No	No	No	No	Yes
QoS-MRCA	Delay-bound	No	Yes	No	No	Yes	No	No	Yes
NSGA-II	Interference-aware	No	Yes	No	No	Yes	No	No	Yes

6. *Jointly CA approaches*: The joint optimization approach can made for each category by solving the CA as the joint optimization problem where take into account multiple objectives, such as interference, topology control, routing, fairness and maximize throughput. Moreover, as seen from Table 6, the joint approaches could use to join the CA with more than one design issues for example, combining the power control of topology control with the one or more CA issues such as interference, routing or fault tolerance.

7. Conclusion

Channel assignment has been used to improve the multi-radio wireless mesh network. In this article, we review the current channel assignment approaches that efficiently utilize the non-overlapping channels to increase the network capacity. Due to the limited number of non-overlapping channels, link optimization become necessary to minimize the number of links sharing a channel, hence, first, we define the CA link optimization approaches. Second, the key design challenges for the CA are identified. Third, the classification of CA approaches is proposed, where the CA approaches are classified into three categories as follows: interference-aware, connectivity-aware, routing-aware. For each surveyed CA approach, we conclude its basic idea, advantage and limitation. Moreover, the overall comparison on these approaches is made for each category. Finally, the categorical comparison and further CA research are point out.

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