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An overview of Channel Assignment methods for multi-radio multi-channel wireless mesh networks

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ABSTRACT

Channel Assignment (CA) is an active research area due to the proliferating deployments of multi-radio multi-channel wireless mesh networks. This paper presents an in-depth survey of some of the CA approaches in the literature. First, the key design issues for these approaches are identified, laying down the basis for discussion. Second, a classification that captures their essentials is proposed. Third, the different CA approaches are examined individually, with their advantages and limitations highlighted; furthermore, categorical and overall comparisons for them are given in detail, clarifying their sameness and differences. Finally, the future research directions for CA are discussed at length.

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1. Introduction

Wireless Mesh Networks (WMNs) have been adopted in many municipal/enterprise area network deployments according to the recent industry white papers [5,32,41]. They are used in a variety of application scenarios such as the last-mile broadband Internet access, campus networks, mobile telephony backhaul networks, and public safety networks. With multiple hops and a mesh topology, the WMN architecture generally consists of three levels as described below.

- The top level comprises one or several gateways, which connect to both the WMN and the wired Internet and forward traffic between these two types of networks. This level can be absent if no Internet access is required and the WMN is only used for local communication.
- The intermediate level comprises numerous mesh routers, which are the vertices in the mesh topology and relay the traffic within the WMN. To enable wide and low-cost deployment, the link and physical layer protocols adopted by mesh routers are international standards such as the IEEE 802.11 protocol [16] or the IEEE 802.16 protocol [17] according to the current practice [5,32,41].
- The bottom level comprises many WLANs or mobile phone cells depending on the usage of WMNs. Either a WLAN or a mobile phone cell generally consists of an Access Point (AP)

and a certain number of wireless clients (e.g., laptops or mobile phones) that are the real producers and consumers of the wireless traffic.

Note that, the gateways and the APs also have the full functionality of the mesh routers besides interfacing with the Internet and the wireless clients respectively, so they both play double roles. And in the study of WMNs, researchers mainly focus on the issues of mesh routers, leaving the Internet or the WLAN/cell issues to other areas of research. In this paper, we also refer to the mesh routers as “nodes” hereafter.

In the initial design of WMNs, the traditional wireless network paradigm is followed, where only one radio (i.e., wireless interface card¹) is equipped at each node and all nodes share a single channel [2,7]. However, several research findings revealed that the capacity per node in such solutions drops significantly with the increase of the network size. For example, researchers in [15] demonstrated that when n identical randomly placed nodes with bandwidth W form a single-channel network, the throughput obtained per node is $\Theta(W/\sqrt{n \log n})$ asymptotically; Ref. [45] demonstrated that in a multi-hop network with all links running the same IEEE 802.11 protocol, the end-to-end performance suffers low throughput and unfairness problems. An intuitive interpretation of the above phenomenon is as follows: in a single-channel multi-hop network, interference can occur not only between nearby flows (known as inter-flow interference)

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¹ In this paper, we use the terms “radio” and “interface” interchangeably, both of which refer to the “wireless interface card”.

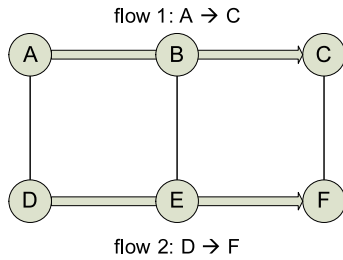


Fig. 1. Inter-flow and intra-flow interference.

but also between the nearby hops in a single flow (known as intra-flow interference), thus significantly degrading the network performance. To illustrate these two kinds of interference, Fig. 1 shows two concurrent flows in a multi-hop network, where not only flow 1 and flow 2 interfere with each other but also hop $A \rightarrow B$ and hop $B \rightarrow C$ in flow 1 interfere with each other.

Due to the above observation, the single-radio single-channel architecture is not appealing. How about the single-radio multi-channel architecture then? It is also considered undesirable because of the following two reasons. First, with only a single radio, a node has to change its channel frequently with the dynamic network traffic so as to fully exploit the multi-channel advantage. Unfortunately, channel switching involves non-negligible delays. For instance, in the IEEE 802.11 hardware, this delay is usually in the order of several milliseconds [36], which is quite significant compared with the transmission delays. Second, with the single radio assigned to different channels to reduce interference, the nodes suffer low connectivity and even disconnectedness. Consequently, it is difficult to provide fault tolerance support or to synchronize neighboring nodes to the same channel if they want to communicate.

Therefore, almost all the current WMN deployments and proposals adopt the multi-radio multi-channel (MR-MC) architecture, where each node is equipped with multiple radios and can use multiple non-overlapping channels. Fig. 2 illustrates the MR-MC architecture with an example mesh network, where each node has two radios and can use four non-overlapping channels that are reused spatially.

As apparent from the current commercial deployments [5,32,41], this MR-MC architecture is practical due to the following two facts:

- (1) The cost of wireless interface cards has dropped rapidly with the proliferation of wireless networks, so the cost of multiple radios is no longer a prohibitive factor.
- (2) The current IEEE 802.11 and 802.16 standards both support multiple non-overlapping channels. For instance, there are twelve non-overlapping channels with 20 MHz center frequency spacing in IEEE 802.11a [18] and three non-overlapping channels with 25 MHz center frequency spacing in IEEE 802.11b [19]. Fig. 3 shows the three non-overlapping channels regulated in US; in Europe, the regulation is only slightly different [19]. For IEEE 802.16, it utilizes radio frequencies of both licensed and unlicensed bands from 2 GHz to 66 GHz² with a flexible channel bandwidth, so it can support significantly more non-overlapping channels than IEEE 802.11 [14]. Therefore, the availability of multiple non-overlapping channels is not an issue as far as the standardization is concerned.

As an aside, [13] recently demonstrated through extensive real-world experiments that there actually exists significant interference between these standard non-overlapping channels in

the current commodity IEEE 802.11 hardware. Nevertheless, Paul et al. also pointed out that this problem can be resolved by using better frequency filters in the hardware for multi-channel use.

The advantages of MR-MC WMNs are obvious. With each node equipped with multiple radios, multiple transmissions/receptions can happen concurrently, which multiplies the throughput. With multiple channels, neighboring links assigned to different channels can carry traffic free of interference, such that the link-layer delay can be dramatically reduced. As a result, when compared with the single-radio and single-channel solution, one of the proposed solutions [36] shows that its multiple-radio and multiple-channel solution improves the network throughput up to a factor of seven, and an industry report [29] claims that its multiple-radio and multiple-channel solution improves the network throughput by a factor of five.

However, the above advantages cannot be fully realized unless a number of issues related to MR-MC WMNs are handled properly. In general, these issues include node deployment, channel assignment, link scheduling, and routing. Among them, the issue of channel assignment (CA), which aims to optimize the MR-MC WMN performance by seeking a proper mapping between the available channels and the radios at every node, has received extensive attention. The CA issue is especially important due to the following reasons:

- It constitutes a new research area for WMNs.
- It is a must-solve problem for the operation of MR-MC WMNs.
- It is challenging because many formulations of the CA problem turn out to be NP-hard.

Therefore, we focus on the CA issue in this paper and present an in-depth survey of the typical approaches addressing this issue. The rest of this paper is organized as follows. The basis for examining these CA approaches, Section 2 specifies the MR-MC WMN model assumed by them and identifies the key design issues that confront them. Section 3 proposes a classification of the CA approaches. Section 4 describes the main idea and basic steps of every surveyed CA approaches individually, points out their advantages and limitations, and makes both categorical and overall comparisons on them. Section 5 presents the future research directions. Finally, Section 6 concludes this paper.

2. Network model and design issues

This section clarifies the network model considered by the surveyed CA approaches and identifies the key design issues for them to address. Besides, this section also gives the necessary background used later in this paper.

2.1. Network model

All the approaches surveyed in this paper assume the following characteristics on the WMNs. Though each approach may bear its own distinct characteristics, the following ones are common.

- (1) The nodes in the WMNs are not mobile.
- (2) At least some of the nodes in the WMNs are equipped with multiple radios.
- (3) Multiple non-overlapping channels (free of inter-channel interference) are available to the network.

2.2. Key design issues

The characteristics in the above model distinguish MR-MC WMNs from other types of wireless networks. Given these characteristics, we identify the following key design issues for the CA approaches to address.

² Not all are available due to the different regulations in different countries.

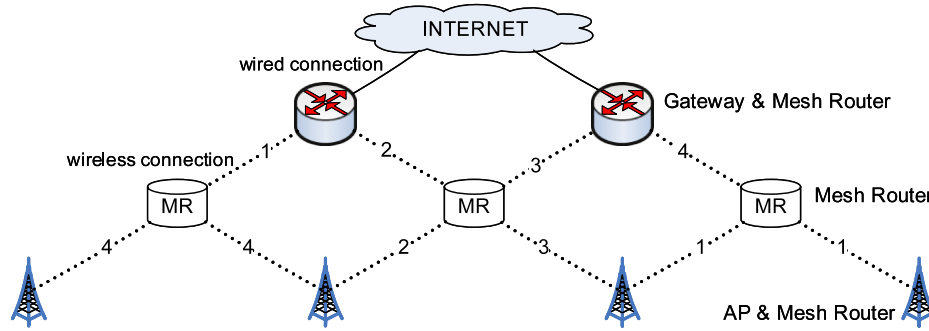


Fig. 2. The MR-MC architecture of WMNs.

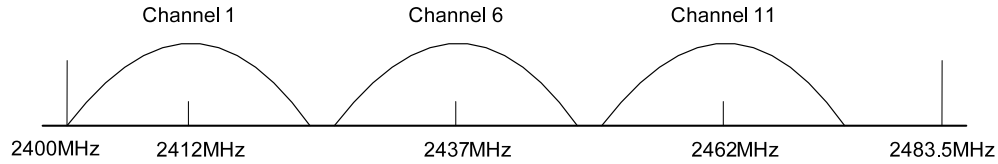


Fig. 3. North America non-overlapping channel selection according to IEEE 802.11b.

2.2.1. Interference

Interference is the foremost factor that degrades the wireless network performance, so the primary goal of CA is to minimize interference within the MR-MC WMNs by utilizing multiple radios and multiple channels. To address the interference issue, a model describing the interference effect needs to be assumed. Currently, there are two widely-adopted models: Protocol Model and Physical Model, both of which are initially proposed in [15].

A very simple one, the Protocol Model can be described as follows: (1) each radio has a transmission range and an interference range, with the former less than the latter; and (2) a transmission from radio X to radio Y is successful if Y is in the transmission range of X and not in the interference range of radios other than X that are currently transmitting. Compared with the Protocol Model, the Physical Model is close to reality but quite complex. It can be described as follows: (1) a transmission is successful if the Signal to Interference and Noise Ratio (SINR) of the transmitter's signal at the receiver is larger than a threshold value; and (2) the interference and noise power at the receiver consists of the noises generated by other ongoing transmissions and the ambient noise in the network. Due to the complexity of the Physical Model, most of the CA approaches surveyed in this paper adopt the Protocol Model (only except [30], which uses the Physical Model).

Besides the interference model, the following constraints related to interference also need to be considered by the CA approaches.

- The number of available channels: due to technical facts or government regulations, the MR-MC WMNs actually cannot use as many non-overlapping channels as needed. Thus, interference cannot be completely eliminated from the MR-MC WMNs.
- The number of radios at each node: it limits the number of non-overlapping channels that can be assigned to each node.
- The node deployment: it determines the geometric distances among the nodes, and hence influences the interference relationship significantly. If the Protocol Model is assumed, the area within which the nodes interfere with each other is actually very large. This is because, to imitate the reality, the interference range is generally considered to be 2–3 times the transmission range. For instance, in both NS2 and QualNet (two popular simulators in use today), the default interference range is approximately twice the default transmission range [44].

So in addressing the interference issue, CA approaches need to consider at least the aforementioned factors: the interference model, the number of available channels, the number of radios at each node, and the node deployment. As to be described later, the joint consideration of these factors mostly results in NP-hard CA problems.

2.2.2. Connectivity

Connectivity is a concept defined on graphs, which are extensively used to model computer networks. To make our later discussion of connectivity issue unambiguous, here we describe and distinguish the following two graph concepts exploited by most of the existing CA approaches: *unit disk graph* and *network topology*. Note that, due to the terminological inconsistency of the literature, these approaches may not use the same terms when they refer to these two graphs.

The *unit disk graph* [9] is widely used to represent wireless networks under the Protocol Model. Specifically, a unit disk graph $G(V, E)$ is defined as an undirected graph where (1) V is the set of nodes in the network and (2) $\forall v_1, v_2 \in V, (v_1, v_2) \in E$ if v_1 is in the transmission range of v_2 (also implying v_2 is in the transmission range of v_1). Note that, as suggested by the name of this concept, an identical transmission range for all nodes is assumed here. This assumption is reasonable in wireless networks because bidirectional communication is necessary in an unreliable wireless link: the sender generally requires an acknowledgement from the receiver after transmitting the data.

While the *unit disk graph* is only concerned with the geometric distances among nodes, the *network topology* [28,34] further models whether any two nodes actually share a common channel as their communication link. Specifically, a network topology $T(V, E)$ is defined as an undirected graph where:

- V represents the set of nodes and E represents the set of actual communication links in the network.
- $\forall v_1, v_2 \in V, (v_1, v_2) \in E$ if one of the v_1 's radios and one of the v_2 's radios share a common channel and they are within the transmission range of each other. Moreover, if the multiple radios at v_1 and v_2 share n common channels, there are n links $(v_1, v_2) \in E$, where n is a positive integer.

According to the above two definitions, the unit disk graph is independent of the channel assignment, but the network topology, on the other hand, is known only when the channel assignment

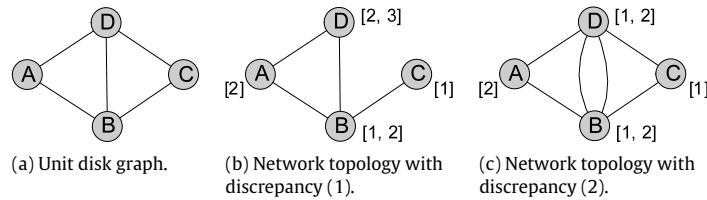


Fig. 4. Two kinds of discrepancies between unit disk graph and network topology.

is done. This difference arises from the *communication constraint* that, in a multi-channel environment, two neighbor radios must share a common channel to communicate. Due to this constraint, altogether two kinds of discrepancies can occur between the unit disk graph and the network topology: (1) a link between two nodes in the unit disk graph is absent in the network topology if the radios on these two nodes are not assigned a common channel; (2) multiple links exist between two nodes in the network topology if multiple common channels are assigned to the radios on these two nodes. These two kinds of discrepancies are illustrated in Fig. 4, where (1) there are three non-overlapping channels available (numbered 1, 2, and 3 respectively), (2) nodes A, C each have one radio and nodes B, D each have two radios, and (3) the channels assigned to these radios are shown inside the square brackets nearby the nodes.

Though the unit disk graph and network topology differ in their structures, they are both important for the CA approaches. The former is usually used as the basis to perform channel assignment, since it is known initially and gives the distance relationship between the network nodes. And the latter is usually used to specify the connectivity requirement for channel assignment, since it embodies the actual communication links.

Therefore, in addressing the connectivity issue in MR-MC WMNs, the CA approaches need to be aware that the CA decisions can actually change the network topology, which is a key difference between the single-channel and multi-channel networks. If the CA approaches ignore this difference, the network topology may be in danger of being disconnected, even though the interference is reduced by distributing channels to different radios. Thus, there is essentially a trade-off between interference and connectivity: the more radios that are assigned to the same channel, the more connectivity is achieved, but the more interference is induced. As to be detailed later, all the approaches surveyed in this paper at least require that the network topology is connected after the channel assignment, while some approaches have stronger requirements. Consequently, how to minimize interference while satisfying the connectivity requirement is an important issue for the CA approaches to address.

2.2.3. Stability

The CA operation can cause two phenomena that undermine the network stability: *ripple effect* and *channel oscillation*. The ripple effect, first described in [36], also arises from the communication constraint described previously. The following example is given to exemplify the ripple effect. Assume interface *I*₂ originally at channel *x* wants to communicate with interface *I*₁ at channel *y*, thus *I*₂ switches to channel *y*. At same time, assume interface *I*₃ is currently communicating with *I*₂ using *x*, so *I*₃ has to switch to *y* to maintain the communication. And such channel change will continue to propagate, if another *I*₄ is currently communicating with *I*₃ using channel *x*. Another problem associated with the ripple effect is that, say in the above example, when *I*₂ switches to channel *y*, some packets may be lost in the communication between *I*₃ and *I*₂ on channel *x*, before *I*₃ switches to channel *y*.

A similar phenomenon to oscillation in routing, channel oscillation means that the channel assignment does not converge and

changes back and forth among several choices. This phenomenon usually happens when the CA is based on a dynamic metric. For example, when two nodes discover that a channel is under-utilized according to such a dynamic metric, they may simultaneously switch to this channel and both begin transmission on it, and then switch back because this channel is now overloaded, as indicated by this dynamic metric. Since channel switching involves significant overhead such as switching delay and traffic interruption, frequent channel switching resulted from oscillation will severely impair the network performance.

2.2.4. Throughput/Latency

Throughput and latency are the two most important measures for network performance. Having a deterministic relationship, they are generally addressed together. To obtain optimal throughput/latency in MR-MC WMNs, the CA approaches need to consider the following two basic strategies. First, reducing interference is almost the most effective method in achieving the optimality, and it is better to make this method adaptive to the dynamic network traffic. Second, links should be treated differently when assigning channels, since different links in MR-MC WMNs impact throughput/latency to different extents. For example, the backbone links carry much more network traffic than the stub links, so they should be given more bandwidth either by assigning more number of concurrent channels or by assigning less interfered channels. In this sense, an MR-MC WMN is analogous to a wired enterprise/campus network consisting of a hierarchy of Ethernet switches, where the ports on an upper-level switch usually have much more bandwidth than the ports on a lower-level switch.

2.2.5. Routing

As shown in Section 2.2.2, the network topology of an MR-MC WMN – a basic factor for making the routing decisions – can be changed by the CA decisions. Thus, routing is dependent on CA. On the other hand, routing can change the traffic load distribution in the network, which is a primary factor considered by CA to reduce the interference dynamically. So in this case, CA is also dependent on routing.

To handle such a relationship between CA and routing, two ways are proposed in the surveyed CA approaches. In one way, CA is viewed as a lower-layer mechanism and does not consider the traffic load, while routing is viewed as an upper-layer mechanism and is fully responsible for distributing the traffic load. Thus, being independent of CA, any routing protocol should be supported by the CA mechanism. In the other way, CA and routing are viewed to be mutually dependent, so they are combined in order to obtain optimal network performance. In the later survey of individual approaches, the routing issue will be discussed further.

2.2.6. Fault tolerance

Though the nodes in MR-MC WMNs are stationary, they can fail because of software or hardware problems. Moreover, the wireless links can also fail due to unexpected scenarios such as external interference or temporary obstacles. So it is necessary for a CA approach to support fault tolerance such that the network can operate in a self-healing fashion. Furthermore, though the multiple

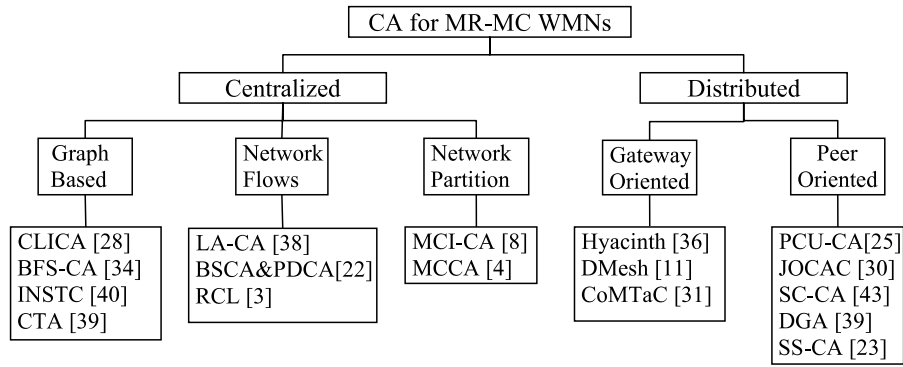


Fig. 5. Classification of CA approaches for MR-MC WMNs.

radios and multiple channels in MR-MC WMNs provide abundant choices for recovering from faults, a selection among these choices has to be made to obtain the optimal results. Therefore, the fault tolerance issue is not an easy task for the CA approaches to address.

2.2.7. Fairness

To obtain the optimal overall network performance, fairness among the nodes is sometimes sacrificed in designing a CA approach. But in many scenarios such as the mobile phone backhaul networks, fairness is a necessary property of the network services. A basic fairness criterion for CA is the capability to avoid that the traffic of some nodes only has access to crowded channels shared by many links, while the traffic of other nodes has access to only partly-occupied channels shared by a few links. Though guaranteeing fairness to certain level introduces additional difficulty to the CA design, it is worth achieving in practice.

2.3. Summary to the key design issues

All the CA approaches discussed in this paper aim to solve some of the above issues. Though these issues are listed separately, they are inevitably related to each other. Some of the issues have mutually-beneficial relationships such as 'less interference results in more throughput' and 'richer connectivity offers better fault tolerance'. However, there also exist trade-off relationships among these issues. For example, reducing interference gives rise to less connectivity, and supporting fairness sacrifices overall throughput. Generally, if both issues with a trade-off relationship are to be addressed, the balance needs to be made according to the requirements of the concrete CA approaches.

We note that channel assignment (or allocation) is also an active research area in cellular networks, where the basic components are the hexagonal cells covering the whole network area. Simply put, the channel allocation problem in cellular networks is how to assign channels to the cells such that adjacent cells use different channels to avoid the interference. Since the cells are connected to the mobile switching center and then to the public switch telephone network via wired links, there is no connectivity issue for the CA in cellular networks. Due to the same reason, the wireless part in cellular networks is not multi-hop, so the CA in cellular networks does not concern the issue of routing. We believe these are the two key differences between the CA in cellular networks and the CA in mesh networks. Limited by the scope of this paper, please refer to [6] for the design issues of CA in cellular networks.

3. Classification of CA approaches

Despite being a nascent research area starting around 2004, CA for MR-MC WMNs has seen many approaches up to now. While possessing considerable similarity, these approaches also exhibit

significant diversity. In this section, we present a classification of the typical approaches surveyed in this paper (see Fig. 5). Note that there can be different classifications according to the different criteria used, and our taxonomy is what we believe the best-suited for capturing the essentials of the CA approaches.

In general, all the CA approaches are classified into two categories: centralized or distributed. For the centralized approaches, a central control is assumed and it has the complete knowledge about the mesh networks. Thus, the formulated CA problems can be solved at a single place. After the result of CA is calculated, it is distributed to the nodes to accomplish. Altogether, we have seen three types of such problems being formulated: the graph-based problem, the network flows problem, and the network partitioning problem. Accordingly, the centralized approaches are classified into three categories using the above problem formulations respectively. The details of the problem formulations and the algorithms proposed to solve them will be detailed in Section 4.

For the distributed approaches, no central control is assumed and each node runs its own copy of the algorithm to assign the channels. They are further classified into two categories according to the traffic pattern being considered: gateway-oriented CA approaches and peer-oriented CA approaches. The former assumes that the main network traffic is to or from the gateways, so the CA can exploit the heuristic that the near-gateway links should be given a relatively high bandwidth. The latter assumes that the network traffic can occur between any pair of nodes with no fixed pattern, so the CA approaches have to be as general as possible to accommodate various kinds of network traffic. The details of these approaches will also be discussed in Section 4.

4. Description and comparison of CA approaches

In this section, we provide a description and comparison of CA approaches based on our classification presented in Section 3. The centralized approaches are examined first, followed by the distributed approaches. For these approaches, we extract their basic ideas, identify their advantages and 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.

4.1. Centralized CA approaches

As mentioned in Section 3, the centralized approaches are classified into three categories according to their problem formulations: the graph-based approaches, the network flows approaches, and the network partitioning approaches. To solve these problems, only a centralized algorithm and no communication protocol is needed. Thus, our classification on the centralized approaches is actually a classification on the centralized algorithms. We observe

that the inputs, the objectives of outputs, and the heuristic or approximation methods are the three characterizing aspects within each category of algorithms. For the inputs, there are many parameters from the networks to consider. Specifically, all the approaches discussed in this section consider some, if not all, of the following parameters as the inputs.

- Node deployment: the geometric position of each node in the network.
- Numbers of radios and channels: the number of radios at each node and the number of non-overlapping channels available at each radio.
- Interference model: all the centralized approaches surveyed in this paper adopt the Protocol Model, with some of them claiming that their schemes can also be generalized to support the Physical Model.
- Traffic profile: the bandwidth of each link and the end-to-end traffic rate of each flow.
- Connectivity constraint: the level of network connectivity to be achieved. All the approaches at least require the *network topology* to be connected after the channel assignment, while some approaches have stronger requirements such as *k*-connectedness in [40].
- Fairness constraint: specifying a certain fairness requirement to be satisfied. For example, [3] requires that λ times the traffic rate of each source node can be routed over the network after the channel assignment, where λ is a constant for all the nodes.

For the objectives of outputs, some approaches aim to maximize the overall throughput, while others aim to minimize the overall interference, etc. Despite different problem formulations, different sets of inputs, and different objectives of outputs, most centralized approaches (only except [8]) surveyed in this paper state or formally prove [28,35,37] that their formulated problems are NP-hard. Consequently, they resort to heuristic or approximation algorithms to get suboptimal results such that the computation complexity is polynomial. Thus, we consider the heuristic or approximation methods as a third characterizing aspect within each category of approaches.

Therefore, when these three categories of approaches are examined in the following subsections, special attention is paid to the three aspects (inputs, objectives of outputs, and heuristic or approximation methods) in contrasting them within each category. The choice of these aspects is actually natural since a well-accepted definition of ‘algorithm’ is ‘a sequence of computational steps to transform inputs into outputs’ [10], which exactly includes these three aspects.

4.1.1. Graph-based approaches

In graph-based approaches, an MR-MC WMN is modeled by a graph with a vertex set and an edge set, and the CA problem is formulated into the problem of assigning channels to vertices or edges in this graph. Three types of graph theoretic concept are generally exploited by this category of approaches: *unit disk graph*, *network topology*, and *conflict graph*. With the first two concepts already described in Section 2, we next describe the concept of a *conflict graph* $G_C(V_C, E_C)$, which was first introduced to the MR-MC WMN context in [20].

The basic ideas of the conflict graph concept are as follows: (1) it is derived from the network topology $T(V, E)$ and models whether two links in E interfere with each other; (2) any link in E is represented by a vertex in V_C ; and (3) if two links interfere, an edge connecting the two corresponding vertices in V_C is included in E_C to show this conflict. With the above said, the definition of *conflict graph* $G_C(V_C, E_C)$ as an undirected graph under the Protocol Model is given as follows:

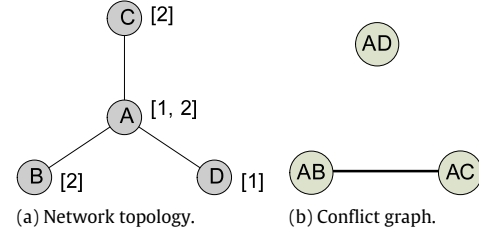


Fig. 6. An example of network topology and its derived conflict graph.

- $\forall (v_p, v_q) \in E$ of T , there is a vertex $v_{p,q} \in V_C$.
- $\forall (v_p, v_q), (v_s, v_t) \in E$ of T (i.e., $v_{p,q}, v_{s,t} \in V_C$), $(v_{p,q}, v_{s,t}) \in E_C$ if (1) v_p or v_q is in the interference range of v_s or v_t , or vice versa and (2) $(v_p, v_q), (v_s, v_t)$ use the same channel.

According to the second condition of this definition, bidirectional communication is assumed here: if either direction of the communication is interfered with, the two links are considered to conflict with each other. To simplify our description, when this second condition is referred to hereafter, we simply say ‘two links interfere with each other’. An example of network topology and its derived conflict graph is illustrated in Fig. 6, where (1) two channels (numbered 1 and 2 respectively) are available, (2) node A has two radios and nodes B, C, D have one radio, and (3) the channels assigned to these radios are shown inside the square brackets nearby the nodes. As shown in Fig. 6(a), there are three links in the network topology, so three corresponding vertices exist in the conflict graph depicted in Fig. 6(b). Since only links AB and AC (both using channel 2) interfere with each other, there is one edge connecting the two corresponding vertices in the conflict graph.

As an aside, in most of the literature, the elements in V and V_C are called nodes and vertices respectively, and the elements in E and E_C are called links and edges respectively. For clarity, this naming convention is followed throughout this paper. Next, four approaches belonging to this category are discussed: (1) Connected Low Interference Channel Assignment (CLICA) [28], (2) minimum INTERference Survivable Topology Control (INSTC) [40], Centralized Tabu-based Algorithm (CTA) [39], and (4) Breadth First Search Channel Assignment (BFS-CA) [34], all of which base their algorithms on the above graph concepts.

(1) Connected Low Interference Channel Assignment (CLICA)

To motivate their problem formulation, Marina et al. propose a new concept called *base channel assignment*, which has the following three characteristics: (1) resulting in a network topology that any link in the *unit disk graph* is preserved and (2) distributing the non-overlapping channels among different links such that the interference is reduced and (3) independent of the traffic pattern and intended for use during the network deployment or a maintenance stage [28].

With the base channel assignment problem as their focus, Marina et al. formulate it into the problem of assigning channels to the links in the unit disk graph (called the connectivity graph in [28]). Specifically, the problem formulation in [28] has the following two output objectives: (1) the two adjacent radios of any link in the unit disk graph are assigned a common channel, and this objective is referred to as the ‘connectivity preservation’ hereafter; (2) the interference over the whole network is minimized in the sense of minimizing the maximum link conflict weight among all links in the resultant network topology. Note that the link conflict weight for a link is defined as the sum of the number of edges incident to the vertex representing this link in the conflict graph.

After proving that the above formulated problem is NP-hard, Marina et al. propose a polynomial time heuristic algorithm named Connected Low Interference Channel Assignment (CLICA) to solve it. The basic ideas of CLICA are summarized as follows:

- Randomly assign a node v the highest priority, then assign other nodes priorities decreasing in the order obtained by depth-first searching the unit disk graph starting from the node v .
- While traversing the nodes in the decreasing order of their priorities obtained above, assign channels to the incident links of these nodes. The operation of assigning a channel to a link includes assigning this channel to both a radio at this node and a radio at the neighbor node. Then, the priorities of unvisited nodes are adjusted according to their *degree of flexibility*, which is the number of channels that a node can choose from without breaking the connectivity preservation. Essentially, the nodes with a lower degree of flexibility will have their priorities increased so that they are visited earlier in the later steps.
- When picking a channel in the above step, a node v_1 picks a channel for its incident link (v_1, v_2) in a greedy manner: a locally optimal choice is made by selecting the channel that minimizes the maximum link conflict weight among all links that can interfere with link (v_1, v_2) . After a channel is assigned to a link, the conflict graph is updated to reflect the new *link conflict weights*.

The proposed CLICA algorithm mainly has two advantages: (1) the paper proves that it achieves the connectivity preservation objective specified in the problem formulation; (2) it is a simple algorithm with a locally greedy heuristic, such that it can be implemented efficiently. The CLICA algorithm mainly has two limitations: (1) by using the unit disk graph to assign channels, the number of radios at each node is difficult to model, so an additional step in the end of the algorithm is needed to deal with these unassigned radios; (2) fairness may be sacrificed because it picks a channel for a link in a locally optimal fashion.

(2) Minimum Interference Survivable Topology Control (INSTC)

INSTC [40], proposed by Tang et al., is similar to CLICA in that it also formulates the CA problem into the problem of assigning channels to links in the unit disk graph. To introduce a metric for minimizing the interference, Tang et al. define a concept called *Link Co-channel Interference (LCI)* for a link in the *network topology*, which means the number of links that interfere with this link in the network topology. Though this definition does not leverage the concept of *conflict graph*, it is equivalent to the concept of *link conflict weight* defined in CLICA. It is worth noting that this equivalence exemplifies that two parallel works sometimes coincidentally define an identical concept using different ways.

With the LCI metric, Tang et al. formulate the CA problem into the ‘minimum Interference Survivable Topology Control (INSTC)’ problem, which is described as follows. Given the unit disk graph G , the number of radios Q at each node, the total number of channels C , and an integer k , seek a channel assignment such that the resultant network topology T satisfies the following two objectives: (1) T is k -connected so that the network is survivable to node/link failures; (2) the interference over the whole network is minimized in the sense that the maximum LPI for all links in T is minimized.

It can be seen that the second objective regarding interference in this formulation is the same as the second objective in CLICA’s problem formulation, since the LPI concept is equivalent to the *link conflict weight* concept. The differences between these two problem formulations are that (1) INSTC requires all nodes to have an identical number of radios Q , while CLICA allows a variable number of radios at each node and (2) INSTC imposes a stronger connectivity requirement by k -connectedness than CLICA, which only requires that any link in the unit disk graph is preserved.

Due to the NP-hardness of the INSTC problem, Tang et al. propose a heuristic polynomial time algorithm (named the INSTC algorithm) to solve it. The basic idea of the INSTC algorithm is to assign the channels by traversing the links in a k -connected

subgraph of the given unit disk graph in a predetermined order. To determine this order, Tang et al. introduce another concept called *Link Potential Interference (LPI)* for a link in the unit disk graph. Simply put, the LPI for a link is defined to be the number of links that interfere with this link in the unit disk graph by only considering the interference range. Then, the links in the unit disk graph is sorted in a non-increasing order of their LPIs, thus obtaining the predetermined order used by the link traversal. As a note, LPI is used instead of LCI to determine the traversal order because the network topology is not known initially and hence the LCI is not available at the beginning of the algorithm.

The behaviors of the INSTC and CLICA algorithms are similar in that they both pick a channel for a link in a locally optimal manner, and are different in that INSTC uses a predetermined order to traverse the links, while CLICA dynamically adjusts its traversal order according to the degree of flexibility obtained from the constantly updated conflict graph.

The main advantage of the INSTC algorithm is that it is proved to be a polynomial time algorithm that achieves k -connectedness, thus the algorithm is efficient and the obtained network topology is robust. Due to its close similarity with CLICA as revealed above, its limitations are the same as those of CLICA.

(3) Centralized Tabu-based Algorithm (CTA)

While CLICA and INSTC formulate the CA problem into the problem of assigning channels to links in the unit disk graph, CTA [39], proposed by Subramanian et al., formulates the CA problem into the problem of assigning channels to the vertices of the conflict graph. In the basic version of CTA, its inputs are the number of radios at each node, the number of channels, and the conflict graph; and its objective of output is to minimize the *total network interference*, which is defined as the total number of edges connecting the vertices in the conflict graph that are assigned the same channels. To consider the multiple radios at each node, the so-called *interface constraint* is enforced in CTA: the number of channels assigned to each node cannot exceed the number of interfaces it has. In the generalization of CTA, the traffic load is also supported as input.

To solve the above CA problem, CTA translates it into the Max K -cut problem, which is generally defined as follows in graph theory: given a graph G , partition the vertices of G into K partitions such that the number of edges whose endpoints belong to different partitions is maximized. Thus, if the vertices assigned a certain channel in the conflict graph is viewed to lie in one partition, the *total network interference* is actually the number of edges whose endpoints belong to the same partitions. In addition, CTA enforces the *interface constraint* to the Max K -cut problem.

Stating that the Max K -cut problem with the added *interface constraint* is NP-hard, CTA resorts to the Tabu search, one of the typical heuristic techniques in genetic computing, to solve it in polynomial time. The main advantage of CTA is that it obtains very close results to the lower bound of the *total network interference* as shown by the authors, and its main limitation is that by assigning channels to the vertices of the conflict graph, in which only one link can be modeled between each node pair, CTA fails to consider the multiple-link case as discussed in Section 2.2.2.

(4) Breadth First Search Channel Assignment (BFS-CA)

As described above, all the previous three algorithms have difficulty in modeling the number of radios at each node by using the unit disk graph or the conflict graph. BFS-CA [34], proposed by Ramachan et al., overcomes this difficulty by introducing the concept of Multi-radio Conflict Graph (MCG), which explicitly includes the number of radios at each node by extending the traditional conflict graph concept. The MCG differs from the traditional concept in two ways. First, it considers links between *radios* as vertices instead of considering links between *nodes* as vertices. Second, it models the interference between links based on

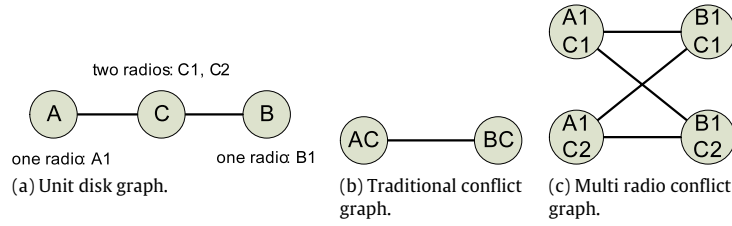


Fig. 7. A comparison of the traditional conflict graph and the MCG.

the *unit disk graph* instead of the *network topology*. As BFS-CA works by assigning channels to the vertices of MCG, the MCG needs to be available at the beginning of the algorithm. The definition of MCG (V_M, E_M) under the Protocol Model is given below.

- For each pair of radios that is adjacent to a link in the *unit disk graph*, there is a vertex representing this link in V_M .
- If two links interfere with each other, there is an edge in E_M connecting the two vertices that represent these two links to indicate this conflict.

To understand this concept, Fig. 7 gives a comparison of the traditional conflict graph and the MCG. Since the conflict graph is actually based on the network topology, we assume here that radios A1, C1, B1 use an identical channel and radio C2 uses a different channel in (a). Thus, only links AC and BC interfere with each other in (b). The MCG for (a) independent of the channel assignment is given in (c), where each pair of radios within transmission range constitutes a vertex, thus there are altogether four vertices representing links and four edges representing conflicts in this MCG. Because radio A1 can only be assigned one channel, links A1C1 and A1C2 cannot exist simultaneously, so they do not conflict with each other, and the same applies to links B1C1 and B1C2.

The problem formulation in [34] makes the following assumptions on the MR-MC WMN environment: (1) there is a gateway in the MR-MC WMN and the major network traffic is to or from the Internet via this gateway; (2) there is a Channel Assignment Server (CAS) running on the gateway, and its task is to collect information from all nodes in the network, calculate the CA results, and distribute the results to all nodes; (3) each node at least has a default radio operating on a common default channel, which can carry both control and data packets; (4) there exist co-located external wireless networks that interfere with this MR-MC WMN, since the MR-MC WMN today mostly use the unlicensed RF bands. With these assumptions, Ramachan et al. formulate the CA problem into the problem of assigning channels to the vertices in MCG such that the following two objectives are satisfied: (1) minimizing the interference among the mesh routers and (2) minimizing the interference between the MR-MC WMN and the co-located external wireless networks.

The advantages of the BFS-CA algorithm mainly include the following: (1) a novel concept of Multi-radio Conflict Graph is proposed, such that it is straightforward to consider the number of radios at each node in designing a CA algorithm; (2) it is claimed in [34] that BFS-CA is the first algorithm considering the external interference, which is a practical problem in the current MR-MC WMN deployments; (3) the practicality of this algorithm is demonstrated by a prototype implementation in a multi-radio IEEE 802.11b testbed. On the other hand, the BFS-CA algorithm has the following two limitations: (1) as seen from step 4 of the BFS-CA algorithm, its heuristic to reduce both internal and external interference by combining the channel ranking and the MCG constraint is intuitive, providing no known bound for the worst-case performance; (2) it is only suitable for the MR-MC WMNs where a gateway acts as the central point of the network traffic.

(5) Summary to the graph-based approaches

As seen above, the four graph-based algorithms all use a certain kind of graph to model MR-MC WMNs and assign channels with a heuristic algorithm. We compare them based on the inputs, objectives of outputs, and heuristic methods in Table 1.

Besides the above comparison table, we also point out the advantages and limitations of the graph-based approaches as a category below.

- Advantage: graph models are intuitive and convenient for designing the CA algorithms.
- Limitation: by solely modeling the network by vertices and edges, it will be difficult to consider traffic load, an important factor for a CA algorithm to improve the network performance.

4.1.2. Network flows approaches

In network flows approaches, an MR-MC WMN is modeled by a flow network, thus overcoming the aforementioned limitation of the graph-based approaches. Network flows is a discipline originated from the 19th century that has applications in many fields. Here we only describe two basic definitions in this discipline: *flow network* and *flow*, which are essential for understanding later discussions. For the details of network flows theory, two classical books [1,10] are recommended.

Specifically, a *flow network* is a directed graph $G(V, E)$ in which each link $(u, v) \in E$ has a capacity $c(u, v) \geq 0$. If $(u, v) \notin E$, then $c(u, v) = 0$. There are two special subsets of V : source set and destination set, denoted by V_s and V_d respectively. A *flow* on the flow network $G(V, E)$ is defined as a real-valued function $f: V \times V \rightarrow R$ that satisfies the following properties:

1. *capacity constraint*: for all $(u, v) \in E$, $0 \leq f(u, v) \leq c(u, v)$. This implies that the traffic rate at a link should not exceed the capacity of this link.
2. *skew symmetry*: if $(u, v) \in E$ and $(v, u) \notin E$, define $f(v, u) = -f(u, v)$; if $(u, v) \notin E$ and $(v, u) \notin E$, define $f(u, v) = 0$.
3. *flow conservation constraint*: for all $u \in V - V_s \cup V_d$, $\sum_{v \in V} f(u, v) = 0$. This implies that, for a node u that is neither in V_s nor in V_d , the aggregate traffic rate entering u should be equal to the aggregate traffic rate leaving u .

To formulate the CA problem into a network flow problem, all the approaches in this category assume the traffic rates (either end-to-end or at each source) are known. In this subsection, we examine three such approaches: (1) Load Aware Channel Assignment (LA-CA) [38], (2) Balanced Static Channel Assignment & Packing Dynamic Channel Assignment (BSCA&PDCA) [22], and (3) Joint Routing and Channel Assignment and Link Scheduling (RCL) [3].

To ease the examination of these three approaches individually, we first provide some of their similarities and differences. Briefly, they have the following two common characteristics.

- Their formulated problems are NP-hard, so all of them propose heuristic or constant-factor approximation methods to solve their problems.

Table 1

Comparison of the four graph-based algorithms.

	Inputs	Objectives of outputs	Heuristic methods
CLICA	<ul style="list-style-type: none"> • The unit disk graph • Number of radios at each node and total number of channels • Interference information described by the conflict graph 	Channel assignment such that any link in the unit disk graph is preserved and the maximum link conflict weight among all links is minimized	<ul style="list-style-type: none"> • Assign channels to the links in unit disk graph • DFS traversal, considering the degree of flexibility to adjust the order • Pick channels greedily according to <i>link conflict weight</i>
INSTC	<ul style="list-style-type: none"> • The unit disk graph • Fixed number of radios Q at a node and total number of channels C • Interference information reflected by LCI and LPI 	Channel assignment such that k -connectedness is achieved and the maximum LCI among all links is minimized	<ul style="list-style-type: none"> • Assign channels to the links in unit disk graph • A k-connected subgraph traversal, using a predetermined order based on LPI • Pick channels greedily according to LPI
CTA	<ul style="list-style-type: none"> • Number of radios at each node and total number of channels • The conflict graph 	Channel assignment such that the <i>total network interference</i> is minimized and the <i>interface constraint</i> is considered	<ul style="list-style-type: none"> • Assign channels to vertices in the conflict graph • Translated to the Max K-cut problem with the <i>interface constraint</i>. And a Tabu search is used to solve it.
BFS-CA	<ul style="list-style-type: none"> • The unit disk graph • Location of the gateway • Number of radios at each node and total number of channels • Internal interference reflected by the MCG • External interference measured by mesh routers 	Channel assignment such that both internal interference among mesh routers and external interference between mesh and co-located wireless networks are reduced	<ul style="list-style-type: none"> • Assign channels to vertices in MCG • BFS traversal, using the distance from the gateway as the guideline • Pick channels greedily according to the MCG and the external interference level

- All of them combine their CA algorithms with routing algorithms. As explained in Section 2, channel assignment and routing are mutually dependent. Specifically for the network flows approaches, the routing algorithms decide the traffic rate at each link, which affects the CA decisions. On the other hand, the CA decisions determine the capacity of each link in the network, which affects the routing decisions. Thus, by combining these two algorithms, the network flow approaches aim to improve the network performance.

Though these three approaches all combine the CA and routing algorithms, they differ in that the first approach uses a loop consisting of the CA algorithm followed by the routing algorithm to make these two algorithms gradually converge to the final results, while the last two approaches jointly address the CA and routing problems by solving a Linear Program (LP).

(1) Load Aware Channel Assignment (LA-CA)

Pioneering the research on centralized CA approaches, Raniwala et al. propose two algorithms for solving the channel assignment problem: *Neighbor Partitioning Scheme (NPS)* and *Load-Aware Channel Assignment (LA-CA)* [37]. The NPS is a very simple algorithm that partitions the neighbors at each node into n groups, where n is the number of radios at each node and can vary at each node. Its goal is that a node communicates with each group of its neighbors using only one radio and one channel, and the way of assigning channels reduces the interference in the network. On the other hand, the LA-CA is a complex algorithm that uses the network flows formulation. We first briefly describe the NPS algorithm because, as an early work, it gives the intuition for solving the CA problem, and then discuss the LA-CA algorithm as our focus.

In NPS, the CA problem is viewed as two subproblems: neighbor-to-interface binding and interface-to-channel binding. Neighbor-to-interface binding determines through which interface a node communicates with each of its neighbors, and interface-to-channel binding determines which channel is assigned to each of the interfaces. To complete these two bindings at each node, NPS randomly starts with one node, say v_1 , and partitions v_1 's neighbors into n groups, where each group has an approximately equal number of neighbors. Then, each group is assigned to one of v_1 's radios and each radio is assigned a currently least-used channel in terms of the number of radios using this channel within the interference range. In turn, each of v_1 's neighbors performs the same procedure, while maintaining the following constraint: the radio used to communicate with v_1 must be assigned the same channel as the one used by v_1 to communicate with this neighbor. This process is iterated until all nodes have partitioned their neighbors. Fig. 8 gives an example channel assignment of a grid mesh network using this algorithm. In this figure, each node has two radios and four channels are used, numbered 1, 2, 3, and 4 respectively.

Next, the LA-CA algorithm is discussed in-depth, with its problem formulation summarized as follows:

- The unit disk graph of the network is known.
- In the unit disk graph, the capacity of each link l , which can use multiple channels concurrently, is determined by (1) the number of non-overlapping channels assigned to l and (2) l 's bandwidth share at each of these non-overlapping channels, where l 's bandwidth share at a channel equals to the bandwidth of this channel divided by the number of links sharing this channel within l 's interference range.

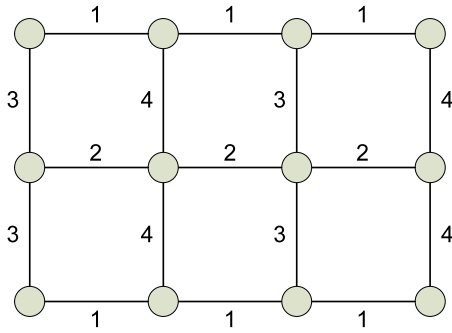


Fig. 8. An example channel assignment of a grid mesh network by neighbor partitioning.

- The end-to-end traffic rates (i.e., traffic loads) for a set of node pairs are known *a priori*.
- The output objective for CA is to ensure that each link's capacity is no less than the aggregate traffic load on it from every node pair.

After formally proving the above formulated CA problem is NP-hard, the LA-CA algorithm uses a heuristic approach to solve it. As mentioned previously, channel assignment and routing are mutually dependent. To break this mutual dependency, LA-CA starts with an estimation of the initial load on each link based on the *a priori* end-to-end traffic rates regardless of the channel assignment, and then iterates the channel assignment step followed by the routing step until the output objective stated above is achieved (see Fig. 9). The basic idea of CA in LA-CA is summarized as follows: the links are visited in the decreasing order of link criticality, which is measured by the amount of traffic load on a link. When a link l is visited, it is greedily assigned a channel that has the least degree of interference, which is measured by the sum of the traffic loads on the links that share the same channel within l 's interference range.

The main advantages of the LA-CA algorithm are that (1) it uses a simple greedy heuristic such that it is efficient to implement and (2) its practicality is demonstrated in an IEEE 802.11b testbed. Its main limitation is that, as acknowledged in [37], it may fail to find a feasible CA result due to the adoption of a simple greedy heuristic.

(2) Common backgrounds for the next two approaches

Since the next two approaches in this category both resort to an LP to solve the formulated network flows problems, their common backgrounds are presented together here.

First of all, both of them incorporate the various CA inputs and the objective of CA output into an LP. The CA inputs mainly include two parts: (1) the inputs related to the definition of a *flow* such as the end-to-end traffic rates and the *capacity constraint* and (2) the inputs arising from the MR-MC WMN environment such as the node deployment, the number of radios at each node, the number of channels available to each radio, and the interference model. And the objective of CA output, such as maximizing the overall network throughput or minimizing the overall network interference, is expressed by the objective function of the LP.

Moreover, both of them propose algorithms for jointly solving the routing, channel assignment, and link scheduling problems in MR-MC WMNs based on their formulated LPs. Two clarifications on this statement are given here. First, 'jointly' means that the three problems of routing, CA, and link scheduling are solved within a single formulation, not that they are solved simultaneously. Actually it can be seen from the later description that, for both of them, the routing problem is solved first to produce the routes for the input *flow*, and then the channel assignment and link scheduling problems are solved based on these routes. For the channel assignment and link scheduling problems, however,

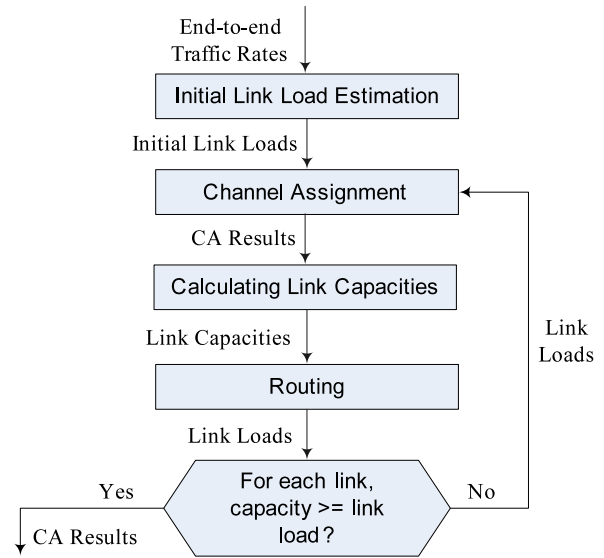


Fig. 9. Flowchart of the combined LA-CA and routing algorithms.

they may be solved either simultaneously or sequentially as to be described further. Second, in their LP contexts, these three problems have the following specific meanings:

- Routing: finding routes for the given *flow* in the given *flow network* $G(V, E)$ such that the constraints included in the LP are satisfied.
- Channel Assignment: assigning channels to each link in E such that the obtained routes are fulfilled under the capacity constraint.
- Link Scheduling: finding the schedule of transmissions for links assigned to the same channel within the interference range, such that no interference occurs and the traffic rates of all routes can be accommodated. Note that, to make link scheduling possible, both approaches assume that all nodes in the network operate in a time-synchronized manner.

(3) Balanced Static Channel Assignment (BSCA) & Packing Dynamic Channel Assignment (PDCA)

Kodialam and Nandagopal [22] formulate the joint routing, CA, and scheduling problem in MR-MC WMNs into a classic network flows problem — the *multi-commodity flow* problem [1]. In their formulation, a set of source nodes transmits to a set of destination nodes and the traffic between each source/destination pair is regarded as a commodity, with its end-to-end rate specified by an element in a rate vector. The LP framework proposed in [22] for solving this problem is flexible. It can not only specify a variety of network inputs such as channels with different bandwidth, but also specify many linear objective functions such as determining the feasibility of a rate vector, maximizing the overall network throughput, or imposing certain fairness constraint.

Under this LP framework, the basic steps of the approach proposed in [22] to jointly obtain the routing, channel assignment, and link scheduling results are described as follows.

1. Determine the feasibility of the given rate vector and solve the routing problem.
2. Based on the routes obtained, both static and dynamic algorithms are proposed to solve the channel assignment and link scheduling problems. Here 'static' means the channel assignment is only decided once and remains unchanged in satisfying the rate vector, while 'dynamic' means the channel assignment can be changed at the beginning of certain time slot to respond to the traffic changes. Because calculating the optimal CA results is NP-hard, both algorithms use a greedy heuristic.

3. The static algorithm is named *Balanced Static Channel Assignment (BSCA)*, which introduces a concept called ‘constraint set’ and tries to minimize the maximum traffic rates on a constraint set when assigning a channel to a link. After the channel assignment, different time slots are assigned to the links that use the same channel within the interference range to avoid interference.
4. The dynamic algorithm is named *Packing Dynamic Channel Assignment (PDCA)*, which defines a time period consisting of n time slots ($n \geq 1$) and performs the channel assignment at the beginning of each period. PDCA uses a greedy packing-based heuristic, in which the links are assigned channels in the descending order of their traffic loads, with each assignment picking the channel that can currently provide the highest bandwidth share. Unlike BSCA, where channel assignment and link scheduling problems are solved sequentially, PDCA solves these two problems simultaneously.

The main advantage of the BSCA&PDCA algorithms is that the adopted LP framework is flexible so that it can incorporate a variety of inputs and objective output functions. And their main limitation is that both of them use a greedy heuristic, such that there is no performance bound in the worst case.

(4) Joint Routing, Channel Assignment, and Link Scheduling (RCL)

Overcoming the above limitation of the heuristic BSCA&PDCA algorithms, Alicherry et al. propose a constant-factor approximation algorithm named ‘RCL’ to jointly solve the routing, channel assignment, and scheduling problems [3]. However, the LP framework of RCL cannot incorporate as flexible inputs and objectives of outputs as that in BSCA&PDCA. Specifically, it considers the following inputs: (1) each node has its own number of radios and there are altogether K non-overlapping channels; (2) all the network traffic is to or from the Internet, which is represented by a single node $t \in V$ in its flow network $G(V, E)$; (3) each mesh router $u \in V$ has an individual traffic rate to t , represented by $I(u)$. And its objective of output is to maximize an identical coefficient λ for every node u such that the multiplied traffic rate $\lambda \cdot I(u)$ can be routed through the flow network. Note that λ is used to impose a fairness constraint, since the main concern of RCL is to achieve fairness among all the nodes rather than to maximize the overall network throughput.

While the background for RCL already described together with BSCA&PDCA, we next summarize the basic steps of RCL as below.

1. Solve LP: To overcome the NP-hardness, this step solves a LP relaxation of the formulated problem, obtaining the routes in the form of a flow $f : V \times V \rightarrow R$.
2. Channel Assignment: This step is based on the observation that the channel assignment is easy to perform if the number of available channels is equal to the minimum number of radios of every node (represented by I_{\min}), since in this case each node can then be assigned all the channels. Accordingly, this step exploits a flow network transformation technique: it first transforms a flow network G into G' where each node has only I_{\min} radios by creating multiple copies of each node; then, it assigns the channels on G' using only I_{\min} channels out of the total K channels available; next, it revises the channel assignment by using the remaining $K - I_{\min}$ channel; finally, it maps the channel assignment back from G' to G .
3. Post Processing: Based on CA from the last step, this step readjusts the flow on the flow network, making efforts to minimize the maximum interference over all channels.
4. Flow Scaling: This step readjusts the flow and CA to make the interference-free link scheduling possible.
5. Interference-Free Link Scheduling: This step schedules the links sharing the same channel within the interference range to use different time slots, while still capable of carrying the flow.

The main advantage of RCL is that it is the only constant-factor approximation algorithm proposed among the centralized approaches that strive to solve an NP-hard CA problem, while all other approaches adopt a heuristic algorithm providing no performance bound. And its main limitation is that the adopted LP framework is inflexible, which can only consider the simple inputs where the traffic rate from each node to the Internet is specified, and a single output objective of maximizing λ such that $\lambda I(u)$ for each node u has a feasible route.

(5) Summary to the network flows approaches

First, we compare the three algorithms surveyed above based on their inputs, objectives of outputs, and heuristic/approximation methods in Table 2.

Moreover, the advantages and limitations of the network flows approaches as a category are summarized as follows.

- Advantages: the traffic load information, which is neglected by graph-based approaches, is inherently included in the network flows formulation.
- Limitations: all the three surveyed approaches assume constant traffic rates, which is not realistic in most practical networks where the traffic pattern is usually bursty and characterized by random on/off sources.

4.1.3. Network partitioning approaches

In network partitioning approaches, the CA problem is viewed as the problem of partitioning the radios and links in an MR-MC WMN into disjoint subnetworks such that each subnetwork uses a single channel and different channels are assigned to these subnetworks to reduce interference. Of all the surveyed centralized approaches, two approaches fall in this category: Matroid Cardinality Intersection Channel Assignment (MCI-CA) [8] and Maxflow-based Centralized Channel Assignment (MCCA) [4].

(1) Matroid Cardinality Intersection Channel Assignment (MCI-CA)

Brzezinski et al. propose MCI-CA in [8], which makes the following assumptions on the MR-MC WMNs:

- The unit disk graph $G_N(V_N, E_N)$ of the network is given, called *network graph* in [8].
- Each node $v \in V_N$ has a certain number of radios, and there are k channels available to the network.
- Interference constraint is given by the conflict graph $G_I(V_I, E_I)$, also called *interference graph* in [8].
- For each link $(i, j) \in E_N$, packets arrive in a stochastic process with an average rate λ_{ij} , which is specified in an arrival rate vector $\Lambda = (\lambda_{ij}, (i, j) \in E_N)$. Note that different from previously-surveyed approaches, MCI-CA uses stochastic processes instead of fixed traffic rates to describe the traffic load information.

As to the network partitioning output, MCI-CA requires the network topology of each obtained subnetwork to satisfy the following objective: *the interference within this subnetwork due to the single channel can be avoided by a stable distributed link-scheduling algorithm*. It is known that not all network topologies can have a stable scheduling algorithm. To find out what kinds of topologies can have such an algorithm, MCI-CA resorts to a recent work [12], which gives the sufficient conditions for the ‘maximal weight scheduling algorithm’ to be a stable algorithm and refers to these sufficient conditions as the ‘Local Pooling (LoP)’. Note that the maximal weight scheduling algorithm can be implemented as a distributed link-scheduling algorithm. To use the maximal weight scheduling algorithm as the stable scheduling algorithm for a single-channel subnetwork, MCI-CA proves that a forest topology satisfies the LoP. Thus, MCI-CA formulates its network partitioning problem (i.e., the CA problem) as follows: *given the above network model, assign channels to each $(i, j) \in E_N$ (i.e., partition the MR-MC*

Table 2

Comparison of the three network flows approaches.

	Inputs	Objectives of outputs	Heuristic/Approximation
LA-CA	<ul style="list-style-type: none"> • Node set and link set • Number of radios at each node and total number of channels • End-to-end traffic rates of a set of node pairs • Protocol Model as interference model 	Channel assignment such that each link's capacity is no less than its traffic load	<ul style="list-style-type: none"> • The links are visited in the decreasing order of their amount of traffic loads • Greedily assign a channel that has the least degree of interference
BSCA & PDCA	<ul style="list-style-type: none"> • Node set and link set • Number of radios at each node and total number of channels • A vector of end-to-end traffic rates • Protocol Model as interference model 	Flexible CA objectives: many linear objective functions related to traffic load and link capacity can be achieved	<ul style="list-style-type: none"> • BSCA greedily picks a channel that minimizes the maximum traffic rates on a constraint set • PDCA greedily picks a channel that can currently provide the highest bandwidth share
RCL	<ul style="list-style-type: none"> • Node set and link set, with a special node t representing the Internet • Number of radios at each node and total number of channels • Source traffic rates from each node to the Internet • Protocol Model as interference model 	Channel assignment that maximizes λ such that $\lambda l(u)$ for each node u can be routed	<ul style="list-style-type: none"> • A constant-factor approximation method • Exploit a flow network transformation technique

WMN network into subnetworks), such that each subnetwork is assigned a single channel and has a forest topology.

MCI-CA solves this problem by reducing it to the *matroid intersection problem*. A concept in combinatorics, a *matroid* is defined as a pair (E, I) , where E is a finite set and I is a set of subsets of E , with each element in I called an *independent set* of E that satisfies the following properties:

- The empty set is independent, i.e., at least one subset of E is independent.
- Every subset of an independent set is independent.
- If $A, B \in I$ and A has more number of elements than B , then there exists an element $e \in A$ and $e \notin B$ such that $\{e\} \cup B$ is an independent set.

And the *matroid intersection problem* is stated as follows: given two matroids $M_1 = (E, I_1)$ and $M_2 = (E, I_2)$, find the largest independent set $A \in I_1 \cap I_2$ of E . For detailed information on matroids, the text [33] is recommended.

For the matroid intersection problems, they can be solved optimally by a known polynomial time algorithm called 'Matroid Cardinality Intersection (MCI)' [26]. However, the forest topologies obtained by MCI vary considerably in size, thus degrading the overall network throughput. To balance the sizes of the forests, MCI-CA proposes the following three algorithms to improve the topologies obtained by MCI and still retain the forest topology: *greedy reallocation algorithm*, *maximum degree reallocation algorithm*, and *average degree reallocation algorithm*, all of which are polynomial time algorithms. Due to the above solution methodology, we refer to the algorithms proposed in [8] collectively as the Matroid Cardinality Intersection Channel Assignment (MCI-CA) for the convenience of reference.

We point out the advantages and limitations of MCI-CA as follows.

- Advantages: (1) it formulates the CA problem into the matroid intersection problem, which is a polynomial-time problem, not an NP-hard problem as in most other approaches, so no heuristic/approximation method is needed; (2) each forest obtained by partitioning can use a distributed link-scheduling algorithm to achieve the stability region.

- Limitations: (1) in case the number of channels is not large enough to assign each partition a unique channel, the stability region in some partitions can only be partially achieved; (2) the partitioning of network topology into forests may not be optimal in terms of overall network throughput; (3) it needs to assume that the network operates in a time-synchronized manner such that the links in a subnetwork can be scheduled with the maximum weight scheduling algorithm.

(2) Maxflow-based Centralized Channel Assignment (MCCA)

Avallone and Akyildiz consider the MR-MC WMNs where the gateways are used to relay all network traffic to the Internet [4]. They model such a WMN by an undirected graph $G_l(V, E_l)$, in which V consists of two types of nodes: mesh routers (no connection to the Internet) and gateways, and E_l consists of the links connecting any two nodes that are within the transmission range of each other. The objectives of their channel assignment approach are three-fold: (1) maximizing the throughput flowing from the mesh routers to the gateways and (2) ensuring the network connectivity by assigning a common channel on both the end nodes of every link and (3) the number of channels assigned to each node does not exceed the number of radios at that node.

The MCCA algorithm is proposed to fulfill these three objectives. For realizing the first one, MCCA first determines the criticality of each link, and then gives the links with higher criticalities more protection against interference when assigning channels. To decide the link criticality, MCCA constructs a *single commodity flow problem* on the initial graph G_l . The purpose of solving this problem is to compute (1) the maximum throughput flowing from the mesh routers to the gateways and (2) the amount of flow that each link must carry to achieve this maximum throughput. After the computation, the amount of flow carried by a link is used as the metric for the criticality of this link.

For realizing the last two objectives, MCCA splits the channel assignment into two stages: *link-group binding* and *group-channel assignment*. In the first stage, all links in the network are partitioned into different groups based on their criticalities. While doing this partition, it is ensured that the number of groups containing the links at a node is not larger than the number of radios at this node. In the second stage, the links of each group are assigned a

Table 3

Comparison of the two network partitioning approaches.

	Inputs	Objective of outputs	Exploited algorithms
MCI-CA	<ul style="list-style-type: none"> • The network graph (i.e., the unit disk graph) • Number of radios at each node and total number of channels • The packet arrival rate vector • The conflict graph 	Partition the WMN into subnetworks, such that each subnetwork is assigned a single channel, and links in each subnetwork can be scheduled by a stable algorithm causing no interference	The Algorithm for Matroid Intersection Problem
MCCA	<ul style="list-style-type: none"> • The unit disk graph, with the set of gateways • Number of radios at each node and total number of channels • Protocol Model as interference model 	(1) Maximizing the throughput flowing from the mesh routers to the gateways (2) Ensuring the network connectivity (3) The number of channels assigned to each node does not exceed the number of radios at that node	The Algorithm for Single Commodity Flow Problem

single channel. The basic idea of this stage is to sort the groups in the descending order of the maximum criticality of all links in a group, and then assign the channels to the groups in such an order. Thus, the groups with high criticality links are considered first and are most likely assigned channels with less interference. Note that (1) since every link is considered in the first stage and every group is assigned a channel in the second stage, the second objective is automatically fulfilled; and (2) since the number of groups at a node is not larger than its number of radios and each group is only assigned a single channel, the third objective is also satisfied.

The main advantage of MCCA is that it naturally realizes its second and third objectives for CA by splitting the CA task into two stages. Its main limitation is that it may not achieve the maximum throughput claimed in its first objective for CA, since it assigns channels simply based on the criticalities of the links.

(3) Summary to the network partitioning approaches

Due to the simple methodology of the network partitioning approaches, they do not generate NP-hard problems, so no heuristic/approximation method is needed. However, they can still be different in the type of known polynomial-time algorithm being exploited. Accordingly, we compare the two algorithms surveyed above based on their inputs, outputs, and exploited algorithms in Table 3.

The advantages and limitations of the network partitioning approaches as a category are summarized as follows.

- Advantage: the network partitioning methodology is straightforward and simple, resulting in polynomial-time problems instead of NP-hard problems.
- Limitation: the approaches in this category are not flexible, since all links in a partition are fixed to a common channel; consequently, they cannot optimally achieve certain objectives such as maximizing the throughput or minimizing the interference in the network.

4.2. Distributed CA approaches

Since the distributed CA approaches involve communication and coordination among multiple parties, they are more challenging to design than their centralized counterparts. In all the eight distributed CA approaches surveyed in this paper, each node measures local channel information and exchanges it with other nodes to calculate the channel assignment. However, these approaches differ in their choices of the local channel information. For instance, these choices can be the number of links sharing a common channel within the interference range, the traffic load on a channel, the signal to interference and noise ratio on a channel, or a combination of them. For convenience, we refer to these choices as CA metrics hereafter. Analogous to the routing metrics that serve as the basis for routing, the CA metrics also play an equivalent role

in making the CA decisions. Therefore, when each CA approach is examined below, special attention is paid to its CA metrics.

According to Section 3, the distributed CA approaches are classified into two categories: gateway-oriented approaches and peer-oriented approaches, which are in turn discussed below.

4.2.1. Gateway-oriented approaches

Gateway-oriented approaches assume a certain number of gateways as the central sinks of the major network traffic. In this subsection, three such approaches are examined: Hyacinth [36], DMesh [11], and CoMTaC [31].

(1) Hyacinth

Pioneering the research in distributed CA approaches, Raniwala and Chueh propose an MR-MC WMN architecture called 'Hyacinth' [36], where the existence of a gateway is assumed and most network traffic is to or from the Internet via this gateway. In Hyacinth, both distributed CA and routing protocols are proposed, and the CA protocol is based on the topology established by the routing protocol, which finds paths for all network nodes to the gateway by establishing a tree topology rooted at the gateway.

The distributed CA protocol originates from the centralized NPS algorithm (see Section 4.1.2) proposed by the same authors, and also views the CA problem as two subproblems: neighbor-to-interface binding and interface-to-channel binding. In neighbor-to-interface binding, each node's network interface cards (NICs) are divided into two classes: (1) UP-NICs that are used to connect to the parent and (2) DOWN-NICs that are used to connect to the children. With this division, the binding of neighbors and interfaces is determined. In interface-to-channel binding, each node only needs to assign channels to its DOWN-NICs, and mandates each of its UP-NICs to use the same channel as the one used by its parent's corresponding DOWN-NIC (see Fig. 10). In order to select a channel for a DOWN-NIC, each node measures the traffic loads on all its channels periodically and exchanges this information via the CHNL-USAGE packets with other nodes in its interference range. Then, each node can calculate the metric for making the CA decisions – the *total load* of a channel, which is a weighted sum of two measures: (1) the total number of links using this channel within the interference range and (2) the aggregate traffic load on this channel from all links using this channel within the interference range. After calculating the *total loads* of all its channels, a node orders these channels according to their *total loads*, thus obtaining the least-used channel.

Besides determining the least-used channel, every node is also given a priority to differentiate their privileges to use channels. Specifically, the priority of a node is defined as its hop distance to the gateway, with a smaller number of hops indicating a higher priority. Combining the total load metric and the priority mechanism, the CA operation in Hyacinth works as follows: in

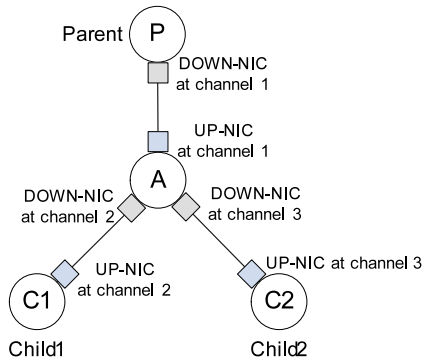


Fig. 10. An example of CA in Hyacinth.

assigning a channel to a DOWN-NIC, a node always chooses the least-used channel that is not currently used by a higher priority node within the interference range. The objectives of this CA operation are twofold: (1) reducing the local interference at a node and (2) offering the near-gateway links higher priorities for choosing channels to obtain higher bandwidth.

As a note, the rationale for the two-step bindings in Hyacinth is to prevent the ripple effect. By mandating that each node is only responsible for the channel assignment at the DOWN-NICs, the propagation of consecutive channel switching is blocked. We view this neat solution of a ripple effect as a major advantage of Hyacinth. And the major limitation of Hyacinth is that when a new node joins the network, a long period of a channel scanning process is needed to discover the DOWN-NIC channels of its potential parents. This process has a length from 5 to 10 s as mentioned in Hyacinth, during which a new node broadcasts HELLO packets at all channels to perform the discovery.

(2) DMesh

While Hyacinth pioneers the gateway-oriented CA approaches, DMesh [11], proposed by Das et al., constitutes a further advance within this category by introducing directional antennas. Specifically, DMesh is an MR-MC WMN architecture where each node has two types of radios: (1) one radio with an omni-directional antenna to transmit control packets as well as data packets in case of fault recovery and (2) multiple additional radios with directional antennas to transmit data packets. The goal of DMesh is to exploit both spatial separation by directional antennas and frequency separation by non-overlapping channels to improve the network capacity.

To be cost-effective, DMesh does not adopt the directional antennas with perfect spatial separation due to their high price. Instead, the directional antennas in DMesh have an interference range in the shape of a cone, and a 45° degree of beamwidth is assumed in the simulations. Thus, a CA protocol is still needed to reduce the interference within the interference cones. In general, the CA in DMesh requires every node to maintain a 'channel map' composed of the following three state vectors: (1) Channel Vector: records whether it uses each channel, (2) Rate Vector: records its traffic rates at each channel, and (3) Destination Vector: records the directional information of the neighbor nodes that it communicates with at each channel. And every node transmits this channel map to its interfering neighbors restricted by directionality, thus exchanging both the traffic and the directional information.

Similar to Hyacinth, the CA in DMesh also stipulates that each node is only responsible for assigning channels to its children. In performing such an assignment, four directional CA schemes are proposed. We give their common basic idea as follows. When a node X attempts to assign a channel to one of its children Y , it first looks for a free channel that is not used by any node whose

interference cone contains X or Y . If such a channel exists, this channel is assigned to Y . Otherwise, X looks for a channel that is the least-loaded in terms of the aggregate traffic rate on this channel (or simply, aggregate number of traffic flows) and assigns it to Y .

The advantages and limitations of DMesh are pointed out below.

- Advantages: (1) both spatial separation and frequency separation are exploited to reduce interference, such that a significant throughput gain, contrasted with an omni-directional solution (termed 'OMesh' in DMesh), is achieved as shown in their simulations; (2) the practicality of DMesh is validated with a 16-node testbed that uses commercial directional antennas.
- Limitations: as mentioned in DMesh, the directions of the antennas are manually positioned during network deployment and remain unchanged during network operation. Thus, a CA protocol that considers steerable directional antennas is more appealing.

(3) Cluster-based Multipath Topology control and Channel assignment (CoMTaC)

As described in Section 2.2.2, the change of channel assignment can change the network topology, thus the network may become disconnected. To solve this issue, Naveed et al. propose an all-in-one scheme called the CoMTaC [31] to address the topology control and channel assignment in a two-phase fashion.

The first phase of CoMTaC focuses on the topology control and runs during the network startup. It consists of two steps. In the first step, the network nodes are grouped into clusters based on their hop distances to the set of gateway nodes in the network. Within each cluster, a *default channel* is used by all constituent nodes on one of their interfaces called the *default interface* to provide the intra-cluster connectivity. And a node bordering several clusters has its second interface tuned to the *default channel* of a second cluster, thus providing the inter-cluster connectivity. In the second step, certain links other than those established in the first step are also established on the non-default interfaces of the nodes, such that the network connectivity is enhanced.

The second phase of CoMTaC focuses on the channel assignment and runs periodically during the network operation. Basically, this phase assigns channels to the links in the network topology established in the first phase, aiming to minimize the interference. It has two parts: (1) assigning channels to the default interfaces and (2) assigning channels to the non-default interfaces. For both parts, the channel assignment is preceded by a process of local interference estimation, which associates a *cost* with each channel. The *cost* is used as the metric to minimize the interference locally.

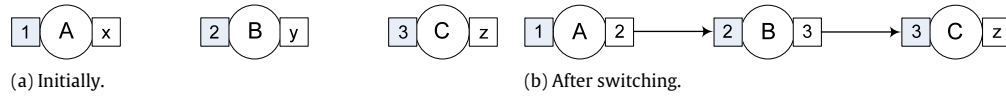
In assigning channels to the default interfaces, only the interference from external sources is considered. For this external interference estimation, each node passively monitors the following two parameters of a channel in a periodical manner: channel utilization and channel quality. Basically, the former is measured by capturing the traffic load on all available channels, and the latter is measured by accessing the *bit error rate* and the *received signal strength* from the lower-layers. Then, each node sends these two parameters to the cluster head, which calculates the *cost* for each channel by combining these two parameters. Finally, the cluster head selects the channel with the least cost as the default channel, and informs it to the other nodes in this cluster.

In assigning channels to the non-default interfaces, the interference of each channel is estimated by the *average link-layer queue length* of the interfaces on this channel. This method is motivated by the following two facts: (1) a large link-layer queue length of an interface is indicative of the high interference on the channel being used and (2) the operation of accessing the packet queue length from the link-layer is simple and efficient. To use this estimation method, each node periodically retrieves

Table 4

Comparison on the CA metrics of the gateway-oriented approaches.

	Metric name	Basic channel information included	Objective
Hyacinth	Total load	(1) The number of links using this channel within this node's interference range	Choose the least-used channel that is not currently used by a higher priority node within the interference range
		(2) The traffic load on this channel within this node's interference range	
DMesh	Channel map	(1) channel vector	Choose the channel that is the least-loaded in terms of the aggregate traffic rate on this channel
		(2) Rate vector	
		(3) Destination vector	
CoMTaC	Average link-layer queue length	The average link-layer queue length of all interfaces operating on this channel within a cluster	Assign the currently least-cost channel that is still available to the interfaces according to the order of their priorities

**Fig. 11.** An example of protocol operation with fixed interfaces and switchable interfaces.

and transmits the link-layer queue lengths of all its interfaces to the cluster head. Then, the cluster head calculates the average queue length within the cluster for each available channel and associates a *cost* to that channel based on the average value. With these channel *costs*, the cluster head assigns the channels to the non-default interfaces of all cluster nodes. The basic operation of this assignment is to prioritize these non-default interfaces, and then assign the currently available least-cost channel to these interfaces according to the order of their priorities. When deciding the priorities for these interfaces, the following three types of interfaces are given higher priorities: (1) interfaces of the border nodes, (2) interfaces with a greater number of neighbors, and (3) interfaces with a smaller hop-distance to the gateway.

The main advantages of CoMTaC are that (1) the network connectivity is ensured by dealing with topology control and channel assignment separately in a two-phase fashion and (2) the interference estimation for a channel by accessing the link-layer queue length is highly efficient. And the main limitation of CoMTaC is that the channel assignment is restricted to the links in the network topology established during the network startup, so it fails to consider all the possible links in the network.

(4) Summary to the gateway-oriented approaches

As seen in the above discussion of the three gateway-oriented CA approaches, the CA metrics play an important role in assigning channels, so we compare the CA metrics adopted by them in Table 4.

Moreover, we highlight the advantages and limitations of the gateway-oriented CA approaches as follows.

- Advantage: the opportunity to utilize the gateway nodes to simplify the CA approach.
- Limitation: the incapability of accommodating other kinds of traffic patterns.

4.2.2. Peer-oriented approaches

Unlike the gateway-oriented approaches, the peer-oriented approaches do not make any assumptions on the traffic pattern, so they are general to accommodate various kinds of network traffic. In this subsection, five such approaches are examined: (1) Probabilistic Channel Usage based Channel Assignment (PCU-CA) [25], (2) Joint Optimal Channel Assignment and Congestion Control (JOCAC) [30], (3) Superimposed Code based Channel Assignment (SC-CA) [43], (4) Distributed Greedy Algorithm (DGA) [39], and (5) Self-Stabilizing Channel Assignment (SS-CA) [23].

(1) Probabilistic Channel Usage based Channel Assignment (PCU-CA)

To prevent the ripple effect, PCU-CA [25], proposed by Kyasanur et al., classifies the interfaces at a node into two classes: *fixed interfaces* and *switchable interfaces*. The channels used by the former are changed periodically by the CA protocol but stay fixed during each period, while the channels used by the latter can change at any time according to the network traffic. Note that the channels used by the fixed interfaces are simply called 'fixed channels' in PCU-CA.

The basic idea of this interface classification is that the fixed interfaces are used to receive network traffic by staying at fixed channels, while the switchable interfaces are used to transmit network traffic by switching to the channels of the fixed interfaces. Of course, if the fixed interfaces at two nodes happen to share the same channel, they communicate with this fixed channel. Because the channels of every node's fixed interfaces stay unchanged in each period, the ripple effect is blocked. An example of protocol operation with the above idea is illustrated in Fig. 11, where each of the three depicted nodes A, B, and C exactly has one fixed interface (indicated by a gray shade) and one switchable interface. Initially, the fixed interfaces of A, B, and C use channel 1, 2, and 3 respectively. At a certain time, assume A has traffic to send to C via B. To accomplish this transmission, A's switchable interface (originally at channel x) switches to channel 2 so as to transmit to B, and then B's switchable interface (originally at channel y) switches to channel 3 so as to transmit to C, resulting in Fig. 11(b).

Corresponding to the two classes of interfaces, the CA protocol proposed in [25] has two parts: assigning channels to the fixed interfaces and switching channels at the switchable interfaces. The CA metric used in the first part is called the *channel usage*, which is measured by the number of nodes using this channel within a two-hop neighborhood (i.e., the assumed interference range). In the protocol operation of the first part, each node maintains two data structures: a NeighborTable that records the fixed channels of its one-hop neighbors, and a ChannelUsageList that records the *channel usage* of each channel. With these two data structures, the basic ideas of CA for the fixed interfaces are summarized as follows.

1. Each node periodically broadcasts Hello packets on all channels to its one-hop neighbors. A Hello packet mainly contains the fixed channels and the current NeighborTable of the sender.
2. Based on the Hello packets received from its neighbors, each node updates its NeighborTable and ChannelUsageList.
3. According to its ChannelUsageList, a node decides whether the number of other nodes using one of its fixed channels is large (a

configurable criterion). If so, it changes this channel to a less-used channel with a probability 0.4 (also configurable), thus preventing the *channel oscillation*, an undesirable phenomenon described in Section 2.

The second part of the CA protocol requires each node to maintain packet queues for each channel with packets to transmit. When a node has packets to transmit to a neighbor, it looks up the NeighborTable to obtain the fixed channel of this neighbor, and then inserts the packets to the corresponding channel queue. The fixed interface is responsible for transmitting packets in the queue of the fixed channel, while the packets in other queues are transmitted by the switchable interfaces. Thus, the channels used in transmission actually depend on the channels assigned to the fixed interfaces, so the first part of the CA protocol determines the channel assignment. Since the first part CA protocol assigns channels based on the channel usage metric in a probabilistic manner, we refer to the entire CA protocol, which is not named in [25], as Probabilistic Channel Usage based Channel Assignment (PCU-CA) for the convenience of later reference.

The advantages and limitations of PCU-CA are given as follows.

- Advantages: (1) both ripple effect and channel oscillation are tackled, thus stabilizing the network; (2) the ‘channel usage’, the number of nodes sharing this channel within two hops, is easy to obtain, thus simplifying the protocol.
- Limitations: (1) despite prevention of channel oscillation, the probabilistic channel switching may not be optimal for the network performance; (2) the traffic load information is not considered, so the criticality of links is ignored in assigning channels.

(2) Joint Optimal Channel Assignment and Congestion Control (JOCAC)

Different from all other CA approaches surveyed in this paper, JOCAC [30], proposed by Mohsenian et al., views the CA problem from a novel perspective: optimizing the performance of TCP congestion control. The rationale for this idea is as follows: if CA does not perform well, interference will cause severe congestion in wireless links, which degrades the TCP performance significantly due to the AIMD algorithm adopted by TCP congestion control. Accordingly, JOCAC formulates the CA problem into the Joint Optimal Channel Assignment and Congestion Control problem and names its proposed algorithm to solve this problem the JOCAC algorithm. Basically, the JOCAC problem is a distributed utility maximization problem for congestion control with the interference modeled by the Physical Model. Below, some background on the JOCAC problem is given first, and then the JOCAC algorithm is summarized.

The distributed utility maximization for congestion control is a general analytic model proposed in [21], which views the network as a set of L links, with each link having capacity c_l ($l \in 1, 2, \dots, L$). There are S sources in the network, and each source s has a transmission rate r_s ($s \in 1, 2, \dots, S$) and a utility function $U_s(r_s)$. To model the congestion control feedback, each link is associated with a congestion price λ_l , and each source is assumed to have access to the aggregate price $q_s(r_s)$ of all the links in its route to the destination. Each source s tries to maximize its profit: $U_s(r_s) - q_s(r_s)$, while the role of congestion price is to adjust the behavior of each source such that the aggregate utility of all sources ($\sum_{s \in S} U_s(r_s)$) is maximized, subject to the link capacity constraint that the aggregate traffic rate from all sources at each link does not exceed the capacity of this link. A key restriction of the above model is that each source or link only needs to measure its local information, such that the model can be implemented in a distributed way. Up to now, many analytical works on TCP congestion control have been done using this model. $U_s(r_s)$ and λ_l for well-known TCP congestion control versions Reno and Vegas are well defined, as summarized in the review paper [27].

Based on the above analytic model and existing definitions of $U_s(r_s)$ and λ_l for TCP Vegas, JOCAC extends these results by incorporating into them the MR-MC WMN parameters such as the number of available channels, number of radios at each node, and SINR at each channel. Thus, the new mathematical expressions of $U_s(r_s)$ and λ_l in the MR-MC WMN environment are obtained, and the JOCAC algorithm that maximizes $\sum_{s \in S} U_s(r_s)$ subject to the link capacity constraint is derived within the new formulation. The basic behavior of JOCAC’s distributed implementation is summarized as follows: each node periodically measures and exchanges with other nodes the local information that mainly includes the SINR and λ_l , and then calculates the CA result using the JOCAC algorithm based on the information measured locally and received from other nodes.

As mentioned in [30], the distinguishing advantage of JOCAC is that it can utilize not only the non-overlapping channels but also the partially overlapping channels.³ This is due to its modeling of interference using SINR, which means that if the SINR is larger than the capture threshold, the packets can be received correctly. That is, the partially overlapping channels can be used, as long as the interference caused by the overlapping frequency bands is not significantly strong. And its limitation is that it introduces a large amount of control traffic in its distributed implementation: each node periodically exchanges information such as SINR and λ_l with all other nodes, since the calculation of CA at each node requires this information along the route for each TCP flow. In this sense, the distributed implementation of JOCAC is similar to the link state routing protocols, where the link states of each node are flooded to the entire network.

(3) Superimposed Code based Channel Assignment (SC-CA)

Xing et al. propose the SC-CA [43], which applies the superimposed code theory to the channel assignment for mesh networks. Established in 1964, the theory of superimposed code has been widely applied in computer science since then. Basically, a superimposed code is a special kind of binary matrix in which the Boolean sum of its columns (called *codewords*) satisfies certain properties, and an s -disjunct code is one category of superimposed code that the Boolean sum of any s codewords in it does not cover any codeword not in that set of s codewords.

The network model of SC-CA is as follows: (1) the N available channels are classified into two categories: *primary channels* and *secondary channels*; (2) a binary N -element vector c_u (called a *channel codeword* or simply a *codeword*) is associated with a node u to label its channels, with value 1 indicating a *primary channel* and value 0 indicating a *secondary channel*; (3) the MR-MC WMN is represented by $G(V, E, C)$, where V is the set of nodes, E is the set of links, and C is a $N \times |V|$ binary matrix (called a *channel code* or simply a *code*) in which each column corresponds to the *codeword* of a node in V . We next summarize the basic ideas of SC-CA as below:

- Given a network G , an s -disjunct code C can be found for G . Before starting, each node in V is allocated a unique codeword from C .
- Each node broadcasts its codeword to its neighbors, and calculates the multiple channels for itself based on the codewords of its own and received from others.
- By exploiting the properties of s -disjunct code, a node always tries to select a channel that minimizes the interference in its neighborhood. The main heuristic for achieving this is to only choose channels from its primary channels that are not being used by its interferers.

³ For instance, in FCC regulation for IEEE 802.11b, there are 3 non-overlapping channels out of the 11 partially overlapping channels.

Table 5

Comparison on the CA metrics of the peer-oriented approaches.

	Metric name	Basic channel information included	Objective
PCU-CA	Channel usage	The number of links using this channel within the two-hop neighborhood of a node	According to the ChannelUsageList, a node periodically switches to a less-used channel with probability 0.4 (configurable).
JOCAC	SINR and congestion price	SINR and congestion price measured locally and received from other nodes	Maximize the utility function for the congestion control
SC-CA	Codeword	An N -element binary vector that labels a node's primary or secondary channels, where N is the total number of available channels.	Minimize the network interference in a node u 's neighborhood mainly by choosing u 's primary channels not being used by u 's interferers.
DGA	local network interference	The number of edges whose endpoints are assigned one channel in the conflict graph within the m -hop neighborhood of a node. (m is configurable)	Minimize the local network interference without violating the <i>interface constraint</i>
SS-CA	Interference cost	The interference level between two possibly overlapping channels measured by their spectral distance	Minimize the sum of the interference costs within a node's interference range

With the ideas above, the following two algorithms are proposed in SC-CA.

- Algorithm 1: output the multiple channels assigned to a node u . This algorithm is mainly designed for the broadcast from u , but the channels obtained can also be used in the unicast from u . SC-CA proves that if for the given s -disjunct code C , $\forall u \in V$, s is not less than the number of interferers of u , this algorithm guarantees interference-free communications.
- Algorithm 2: output the channel assigned to a directed link ($u \rightarrow v$). This algorithm is only designed for the unicast on a link ($u \rightarrow v$). SC-CA proves that if for the given s -disjunct code C , $\forall u \in V$, s is not less than the number of one-hop neighbors of u , this algorithm guarantees interference-free communications.

The main advantages of SC-CA are that (1) both Algorithm 1 and 2 only require codewords information from at most two-hop neighbors, so they are localized and involve low communication overhead, and (2) in certain conditions described above, both algorithms can achieve interference-free communications, and (3) the channel assignment for broadcast is addressed in algorithm 1, which is overlooked by most of other CA approaches. The main limitations of SC-CA are that (1) though it is theoretically sound, it models the interference basically by the Protocol Model, which is not very realistic and thus limits its use in practice, and (2) the performance of SC-CA is not compared with other CA approaches.

(4) Distributed Greedy Algorithm (DGA)

The problem formulation of DGA is the same as CTA, which is surveyed in Section 4.1.1. Both algorithms are proposed by Subramanian et al. in [39]. Recalling from Section 4.1.1, the CA problem is translated to the Max- K -cut problem with the added *interface constraint* in [39]. To solve it in a distributed manner, in which the global information is not available at an individual node, DGA resorts to a greedy heuristic that only uses local information. The basic idea of this heuristic is as follows. Let u denote the vertex in the conflict graph corresponding to the link (i, j) , k denote a channel in the set of all channels, and m denote the number of hops, a configurable parameter. u is said to be owned by node i or node j , whichever has the higher node ID. At an arbitrary node i , it selects a (u, k) pair based on the channels used in its m -hop neighborhood, such that (1) the pair (u, k) results in the largest decrease in the local network interference of its m -hop neighborhood and (2) assigning k to u does not violate the *interface constraint*. Also recalling from Section 4.1.1, the local network interference is defined as the number of edges whose endpoints are assigned one channel in the conflict graph within the m -hop neighborhood of a node.

The main advantages of DGA are that (1) the distributed execution of DGA is proved to guarantee stabilization and (2) despite

the simple greedy heuristic with only local information, DGA still obtains very close results to the lower bound of the *total network interference* as shown by the authors. The main limitation of DGA is that it is not very scalable, since the total number of iterations for it to stabilize is in the order of $O(V_C \cdot K)$, where V_C is the total number of vertices in the conflict graph and K is the total number of available channels. Representing the total number of links in the network, V_C will become a very large number when the total number of nodes in the network increases.

(5) Self-Stabilizing Channel Assignment (SS-CA)

The design of SS-CA [23] is inspired by its authors' previous theoretical work on a distributed self-stabilizing protocol for replica placement [24], of which the main idea is to place the replicas "far" from each other. In adapting this replica placement approach to the channel assignment problem, SS-CA views the *channels* as the *replicas*, and more attention is given to the practical issues that are ignored in [24].

Instead of assuming orthogonal channels, SS-CA supports overlapping channels in the mesh network, and measures the interference between any two channels by the *interference cost function* $f(a, b)$, or simply *interference cost*. Basically, $f(a, b)$ is only concerned with the spectral distance between a and b , and is not affected by the spatial distance between the two nodes using a and b , as long as they are within the interference range of each other. In the testbed implementation of SS-CA, $f(a, b)$ is defined to have a linear relationship with the spectral distance of a and b , taking value 0 when a and b does not overlap, and reaching its maximum when a and b are identical.

Using the *interference cost* as the channel metric, SS-CA designs a *channel selection algorithm* executed at a single node. In this algorithm, a node greedily selects a channel that minimizes the sum of the *interference costs* within this node's interference range. For the stabilization of this algorithm, when a node changes its channels, this node should have the correct information about other nodes' current channels. However, this condition may not be true in the real networking environment where there exist delays in exchanging messages. Based on the aforementioned theoretical work [24], SS-CA solves this coordination problem by designing a stabilization-guarantee protocol that (1) runs the *channel selection algorithm* at a node and (2) exchanges channel information among the nodes within the running node's interference range and (3) exploits distributed mutual-exclusion operations to coordinate the channel changes. For the details of this provably self-stabilizing protocol, SS-CA refers the readers to [24].

The main advantages of SS-CA are that (1) it involves a low-overhead since each node in it greedily selects channels using a

simple local objective function – the *interference cost function* and (2) the self-stabilization of the channel assignment is guaranteed by the proposed algorithm and protocol and (3) a real 14-node testbed implementation is conducted to validate it. The main limitation of SS-CA is that in the interference cost function, only the spectral distance and no spatial distance is considered in calculating the interference among the two possibly overlapping channels, which is not accurate in reality.

(6) Summary to the peer-oriented approaches

We compare the CA metrics adopted by the five peer-oriented approaches in Table 5.

Moreover, we highlight the advantages and limitations of the peer-oriented CA approaches as follows.

- Advantage: the capability of adapting to various kinds of traffic patterns, making it applicable for most of the current WMNs, where the peer-to-peer traffic is also a major part of the total network traffic.
- Limitation: the difficulty of dealing with CA issues such as fault tolerance, ripple effect, and channel oscillation without any assumption on the traffic pattern.

4.3. Summary to all CA approaches

In the previous two subsections, we have surveyed state-of-the-art centralized and distributed approaches, with their advantages and limitations identified each. As an overall summary to these approaches, we next present a comprehensive table that compares and contrasts them based on ten basic properties (see Table 4). Reflecting which approach is suitable or unsuitable in which condition, these properties are listed as follows, with their labels indicated within parentheses:

1. A default common channel is used to transmit control messages. (DeCh)
2. Traffic load information is considered. (TrLd)
3. The existence of gateway nodes is required to facilitate CA. (GW)
4. The Physical Model is adopted as the interference model. (PhMo)
5. Ripple effect is addressed. (RpEf)
6. Channel oscillation is addressed. (ChOs)
7. Routing scheme is proposed in combination with CA. (Rtng)
8. Fault tolerance is supported. (FaTo)
9. Fairness is supported. (Fair)
10. Real testbed implementation is conducted. (Tbed)

The selection of these properties is justified as follows. For property 1, a default common channel provides a convenience to address the connectivity, stability, and fault tolerance issues, but it incurs hardware overhead and consumes a frequency band. For property 2, considering traffic load information enables the CA results to adapt to the current network situation, but makes the CA operation complex. For property 3, exploiting gateway nodes eases the CA design at the price of sacrificing generality. Properties 4–9 are selected from the key design issues identified in Section 2, with their meanings described and their importance justified there. Property 10 is concerned with real testbed implementation, which shows the practicality of the corresponding CA approach. Note that two key design issues identified in Section 2 are not included in the above properties (i.e., connectivity and throughput/latency), since they are imperative for any CA approach to address, thus omitted.

In Table 6, the names of the distributed approaches are shown in *italic*, so as to be distinguished from the centralized ones. If an approach satisfies/dissatisfies a property, the corresponding table entry is marked by Yes/No respectively. If a property cannot be applied on an approach, the corresponding table entry is marked

by N/A (Not Applicable). For example, due to the static nature of the centralized approaches, there are no ripple effect and channel oscillation issues in them, so all the corresponding entries are marked by N/A.

This table provides the following additional understandings to the current CA approaches besides the summarizations given in the previous subsections.

- Properties 4 and 6 are only addressed by a few approaches, which shows that the two corresponding issues – Physical Model and channel oscillation – receive very limited attention from the current CA research. Accordingly, these two issues are further discussed in the next section about future research directions.
- Property 8 is supported by all of the distributed approaches and none of the centralized approaches, which shows that the distributed approaches can adapt to the network dynamics while the centralized ones do not have such capability.
- According to the criterion on fairness for CA described in Section 2, if an approach explicitly shows the support of fairness or considers the traffic load while performing CA, we regard it as supporting fairness, otherwise not. As a result, more than half the approaches provide such fairness support, showing that fairness has received adequate attention from the current approaches.
- Real testbed implementation is conducted by five approaches, showing that the current research efforts are increasingly attaching importance to the practicality of their proposals. This trend is especially beneficial for the protocols in wireless environment, where the modeling of physical channels is still immature and only real implementations allow the protocols to be tested upon various channel uncertainties.

For the two broad categories of CA approaches (centralized and distributed), we also summarize their advantages, limitations, and application scenarios in Table 7.

5. Future research directions

In this section, we first foresee the general research directions for CA, and then pinpoint some specific research directions.

For the general research directions, we first argue that more research effort should be put into the distributed CA approaches, because (1) the distributed approaches are needed by the practical MR-MC WMN networks, which exhibit considerable network dynamics such as nodes/links failure, traffic load changes, and external interference and (2) all of the specific future research issues to be discussed below require further attention from the distributed approaches. A second general research direction is to consider a more realistic physical layer in the CA design. As shown in Table 6, most current CA approaches only consider the Protocol Model as the interference model, which is not very realistic. We believe that using the signal strength instead of the predetermined interference range to decide the channel status is a more desirable method in future. Two signal strength metrics obtainable from the physical layer are the RSSI (Receive Signal Strength Indicator) suggested by the measurement study [13] and the SINR used in the JOCAC [30].

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.

- External Interference: since the communication in MR-MC WMNs uses the IEEE 802.11 and 802.16 standards that operate in the unlicensed RF bands, there is no guarantee that other external wireless sources do not use the same bands. In some of the current MR-MC WMN deployments [5,32], the status of all employed channels is constantly monitored by the radios at

Table 6

Comparison of all CA approaches.

	1. DeCh	2. TrLd	3. GW	4. PhMo	5. RpEf	6. ChOs	7. Rtnng	8. FaTo	9. Fair	10. Tbed
CLICA	No	No	No	No	N/A	N/A	No	No	No	No
INSTC	No	No	No	No	N/A	N/A	Yes	No	No	No
CTA	No	Yes	No	No	N/A	N/A	No	No	No	No
BFS-CA	Yes	No	Yes	No	N/A	N/A	No	No	No	Yes
LA-CA	No	No	Yes	No	N/A	N/A	Yes	No	No	Yes
BSCA & PDCA	No	Yes	No	No	N/A	N/A	Yes	No	Yes	No
RCL	No	Yes	Yes	No	N/A	N/A	Yes	No	Yes	No
MCI-CA	No	Yes	No	No	N/A	N/A	No	No	Yes	No
MCCA	No	Yes	Yes	No	N/A	N/A	No	No	No	No
<i>Hyacinth</i>	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
<i>DMesh</i>	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
<i>CoMTaC</i>	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No
<i>PCU-CA</i>	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No
<i>JOCAC</i>	No	Yes	No	Yes	No	No	No	Yes	Yes	No
<i>SC-CA</i>	No	No	No	No	Yes	Yes	No	Yes	Yes	No
<i>DGA</i>	No	Yes	No	No	No	No	No	Yes	No	No
<i>SS-CA</i>	Yes	No	No	No	No	No	No	Yes	No	Yes

Table 7

Advantages and limitations of the centralized and distributed approaches.

	Advantages	Limitations	Application scenario
Centralized	Capable of getting the optimal or near-optimal CA results, due to the availability of entire network information.	Assume stable nodes/links and static traffic pattern, due to the difficulty of gathering and distributing information globally in an MR-MC WMN.	During network deployment or maintenance stages
Distributed	Capable of quickly adapting to network changes and failures, because of only relying on the local information.	CA results may be far from global optimality, due to the use of only partial information.	During network operation stage

each node, and if external interference is detected by a radio, the channel assignment mechanism at the node can dynamically switch this radio to a new channel. In the surveyed approaches, only [34] considers 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. Therefore, more research effort should be devoted to avoiding external interference in designing the CA approaches in future. 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.

- **Directional Antennas:** in the surveyed approaches, only DMesh [11] considers directional antennas, but imperfect directionality is assumed, so it still addresses the interference within the interference cones. With the hardware price continuously decreasing, directional antennas with strict directionality will be prevalent in future. Therefore, designing CA with the interference issue simplified by the directional antennas should be considered by future research to improve the network performance.
- **Channel Oscillation:** to address this phenomenon, PCU-CA [25] uses a probabilistic channel switching mechanism, which prevents channel oscillation but may not be optimal for the network performance. In light of this, we suggest that the techniques used to solve the routing oscillation can be borrowed with certain adaptation to tackle the channel oscillation. To name some such techniques, a hysteresis factor is used to avoid an overlay route flap in [46], and limiting route advertisements by fixed timers is used to damp the BGP route flap in [42].
- **Quality of Service (QoS):** QoS is needed by some major WMN applications such as VoIP and video surveillance [5,32,41]. Unfortunately, no CA approaches surveyed in this paper include QoS constraints in their problem formulations, though some of them address QoS in their combined routing algorithms. Similarly, the current MR-MC WMN deployments [5,32,41]

also only provide QoS support in layer-2 frame forwarding or in layer-3 packet routing, where the frames/packets can be classified and thereby treated differently. This leads to the natural question whether CA is the proper place to implement QoS functionality. To this question, our answer is that CA should provide QoS support since it decides the bandwidths of network links, which are the fundamental resources for providing QoS. Though CA does not deal with the packet forwarding directly, it should be designed to have QoS in mind, thus supporting the bandwidth allocation requirement needed by the packet forwarding components in the layer-2/3 protocols. For example, one kind of QoS support CA can offer is to guarantee that the bandwidth of each link is no less than a threshold value.

6. Conclusion

With the fast advance of wireless technologies nowadays, the WMNs have evolved from a single-radio single-channel architecture to an MR-MC architecture. Adopted in many WMN deployments, this MR-MC architecture launches a new research area — channel assignment, which seeks to find the optimal mapping between the channels and radios at each node to improve the network performance.

In this paper, considerable effort is made to provide insight into the state-of-the-art approaches proposed in the CA research area. Our contributions are fourfold. First, the key design issues for CA approaches are identified, with the their importance elucidated. Second, a classification of the CA approaches is proposed, where the CA approaches are classified into two categories in general: centralized and distributed. The centralized approaches are further classified according to their problem formulations, and the distributed approaches are further classified according to their assumed traffic patterns. Third, each CA approach is treated with a summary of its underlying idea, followed by the remarks on its pros and cons. Also, both categorical comparisons and overall comparisons on these approaches are made, manifesting their sameness and differences. Finally, both general and specific directions for future CA research are pointed out, with solution hints given.

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