Wireless mesh Networks having Topology Control in Multi-Channel, Multi-Radio

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ABSTRACT: Wireless mesh network is a technology to handle different types of application in different scenarios. Now a days it turns toward a multi-radio multi-channel (MR-MC) WMN architecture, by which we can improve network performance by equipping each node with multiple radio interfaces and by using multiple non-overlapping channels. This provides a great scope in network design. Specifically, topology control (TC), one of the fundamental research topics in WMNs, has also received attention in MR-MC WMNs. This article presents an overview of topology control mechanisms in the existing literature with emphasis on the mutual dependence of TC on other networking issues such as power control, channel allocation, routing, and directional antennas.

I. INTRODUCTION

Wireless mesh networks (WMNs), with multiple hops and mesh topology, has been emerged as a key technology for a variety of application scenarios including broadband home networking, community networking, business organization networking, and metropolitan area networking [1]. It provides an alternative way to deploy broadband network infrastructures to local communities at low cost. However, the deployment of wireless mesh networks has a major challenge, which is throughput scalability. As illustrated in Fig. 1, the general architecture of WMNs is composed of three distinct wireless network elements: mesh gateway (mesh routers with gateway/bridge functionalities), Mesh routers (access points) and Mesh Clients (mobile devices). Mesh clients connect to mesh routers using a wireless or a wired connections. Every mesh router performs forwarding of data for other mesh routers, and certain mesh routers also have extra capability of working as gateways for networks. Such gateway routers often have a wired connection which carries the traffic between the mesh routers and the Internet.

The self-organization, self-healing, self-configuration, easy deployment, easy maintenance, and cost effectiveness feature are some advantage of WMNs. The WMNs inherit almost all characteristics of more general wireless ad hoc networks (e.g., decentralized design, distributed communications). Unlike the mobility of ad hoc nodes, mesh routers are normally fixed. Therefore, ad hoc networks are normally energy-constrained, and energy efficiency which is usually a target of design. Whereas mesh routers have no limitations regarding energy consumption.
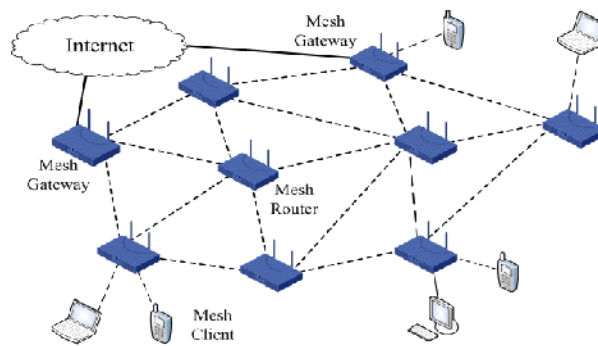

Fig. 1. Wireless mesh network architecture with mesh gateway, mesh routers, and mesh clients.

Traditional WMNs operate in single-radio single-channel (SR-SC) architecture where each mesh router has only one NIC card and all the mesh routers share one common radio channel. In such a networking , the network suffers from low performance and capacity due to frequent packet collisions and back offs, especially for real-time applications such as VoIP transmission across   multi hop WMNs [2,3]. In fact, the IEEE 802.11b/g bands and the IEEE 802.11a band assign 3 and 12 non-overlapping frequency channels, respectively. Though still there exist significant interference between these standard non-overlapping channels in the current IEEE 802.11 hardware, this problem can be handled by providing better frequency filters in hardware for multi-channel use. So, the use of single-radio multiple-channels (SR-MC) has been proposed to enhance the performance of WMNs [4,5]. Compared with the SR-SC architecture, the SR-MC architecture can help to reduce the interference and increase network performance. A required function of the SR-MC solutions is there for each router to dynamically switch between channels along with dynamic network traffic, while coordinating between neighboring nodes to ensure communication on a common channel for some period. However, this type of coordination is usually based on tight time synchronization between nodes, which is difficult to realize in a multi hop WMN. Moreover, fast channel switching capability (in the order of $100 \ \mu s$) is not yet available with commodity hardware. It is noted that the latency in switching the channels with the use of commodity hardware 802.11 NICs can be up to 100 ms [6,7]. An   solution to overcome high latency problem and at the same time to improve performance of WMN would be using a Multi-Radio Multi-Channel (MR-MC) architecture. In such architecture, every mesh router is equipped with multiple NICs and each NIC can operate on multiple frequency channels. In MR-MC architecture, multiple transmissions/receptions can occur concurrently, and neighboring links allocated to different channels can carry traffic free from interference. However, MR-MC architecture use poses some new issues. In general, these issues include topology control, power control, channel allocation, link scheduling, and routing. Among them, the issue of topology control (TC) has received more attention. TC is one of the fundamental research area in WMNs. When designed properly, it can help to enhance the operation of WMNs on good connectivity, enhance energy efficiency, mobility resilience, improve network capacity, reduce interference, etc. In MR-MC WMNs, TC is dependent on power control, channel allocation, and routing, which creates new design challenges on its design. With the goal of improving performance of multi-hop wireless networks, in the recent years great attention has been given to networks where each node is operated with multiple radio interfaces and can operate on multiple channels. This new degree of freedom has been proved to potentially allow for enhance capacity with respect to single-channel single interface networks. This approach is particularly successful if applied to 802.11 networks, since multiple channels are already exists and devices provided with multiple wireless networking cards are being designed and already developed in some test beds.

Therefore, we discussed the TC-related issues for MR-MC WMNs in this article and present an overview of typical TC mechanisms in the literature. The remaining article is organized as follows. Section 'Multi-radio multi-channel (MR-MC) WMNS' discusses about the technology of MR-MC WMNs. In Section 'Challenges on topology control in MR-MC WMNS', we describe the challenges faced by TC in MR-MC WMNs. Section 'Review: Topology control mechanisms for MR-MC WMNS' describes and compares main TC-related mechanisms that have been given in the existing literature. Section 'Future research directions' presents future research in this area. On end, Section 'Conclusions' concludes whole article.

II. WMNS HAVING MULTI-RADIO MULTI-CHANNEL (MR-MC)

Traditional multi-hop wireless networks have almost exclusively composed of single radio elements. It is due to the wireless interference severely limits   network capacity in multi-hop settings. With use of multiple channels and multiple radios provide an chance to break down the conflict and shift the interfering transmissions to non-overlapping channels. Indeed,   this concept facilitates by several technologies. For example, in some WMNs, a mesh router connected to clients in its cell using   802.11b radio on a 2.4GHz channel, and communicate to other routers using an 802.11a radio on 5GHz channel. In open spectrum system, unlicensed users are allowed to share spectrum with legacy users, thereby using multiple spectrums to create new capacity.

III. CHALLENGES

The new challenge of channel assignment arises in such multi-radio multi-channel wireless mesh networks (WMNs). The channel assignment algorithm decides on which channel   transmission should take place. A delicate algorithm success this new degree of interference avoidance by allocating orthogonal channels to simultaneously active links in the same conflict set.

In WMNs, the user learned that throughput is the end-to-end flow throughput. Therefore, the channel assignment algorithms aim should be end-to-end metrics. It has been shown in current references that maximizing link based metric may not essentially results to maximum end-to-end metrics.

On the other hand, the optimal channel assignment strategy would also based on medium access control as well as routing decisions. In many cases, the combined solution of MAC, channel assignment and routing is much so much costly. A feasible channel assignment algorithm should have loose coupling (i.e. passing some cross-layer information) with other layers to keep the runtime complexity as much lower as possible.

In MR-MC WMNs, each mesh router has multiple NICs and each NIC can operate with multiple frequency channels. In experimental MC-WMN test-beds in [6,8], each mesh router is has two NICs. Giving up to four NICs is also considered reasonable [6,9]. Figure 2 illustrates an example of an MR-MC WMN with six wireless mesh routers, three NICs for each router, and five frequency channels. The label number defines the assigned channels that are reused spatially.
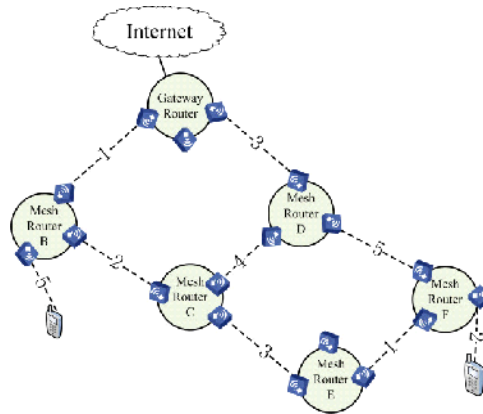

Fig. 2. Example of an MR-MC WMN (six wireless mesh routers, five frequency channels, and three NICs per mesh router).

The MR-MC network solution has attracted lots of attention with the benefits of reduction in interference and improvement in network scalability in wireless mesh networks. Nevertheless, the MR-MC model also arises technical issues to be dealt with [10]. As mentioned earlier, the number of available channels is limited to 3 or 12 in IEEE 802.11 frequency bands. This implies that some logical links may be assigned to the same channel. In such case, interference occurs if these logical links are closer to each other, and so these interfering links cannot be active on same time. Furthermore, the number of available NICs are also limited, and hence some logical links within a router require to share a NIC to transmit and receive the data packets. When two logical links within a router share single NIC, they are required to operate on same frequency channel, and cannot be activate on same time. So, it significantly reduces their effective capacity. The effective link capacity can be enhanced by removing some of the links from their logical topology. However, when some links are not active, the number of hops through some routing paths may be increased and the logical topology may not even be connected. Therefore, how many number of logical links should be allocated between neighboring routers, how to assign interfaces and channels, and through which logical links packets should be forwarded need to be considered in MR-MC WMNs.

Furthermore, the physical topology of the routers and other constraints in MR-MC WMNs, four important issues that needs attention are summarized in [10], i.e., logical topology formation, interface assignment, channel allocations, and routing decisions. Logical topology defines the set of logical links and network connectivity. Interface assignment decides how logical links should be assigned to the NICs in every wireless router. Channel allocation selects the operational channel for each logical link. Finally, routing decision defines through which logical links packets should be forwarded.

Considering the above discussed issues with the MR-MC architecture, existing communication protocols, ranging from routing, MAC, and physical layers, need to be revised and enhanced. In physical layer, techniques mainly focus on three research areas: enhance transmission rate, enhancing error resilience capacity, and increasing reconfigurability and software controllability of radios [11]. In order to improve the capacity of wireless networks, many high-speed physical techniques, such as OFDM, UWB, and MIMO, have been discovered.

To enhance error resilience, many channel coding schemes have been discovered, and adaptive channel coding schemes and cognitive radios are require to utilize the wireless spectrum more efficiently.

In MR-MC WMNs, the cost of wireless radios with multiple transceivers is s very high, thus it is essential to optimize the hardware design so as to decrease the cost. Moreover, directional antennas have been considered to be used in MR-MC systems. Besides all these, power control is another interesting concept that should be thoroughly investigated, since allocating optimal power for controlling the topology can decrease interference and helps in improving overall network performance.

In MAC layer, depending on which network node take responsibility of the coordination of medium access, MAC can be categorized into two major types: centralized MAC and distributed MAC. In WMNs, due to its distributed nature, distributed MAC is preferred. The MAC protocols for WMNs can be classified into two types: single-channel and multi-channel MAC protocols [12,13]. Designing an effective distributed multi-channel MAC protocol for MR-MC WMNs is a much more difficult task. In MR-MC WMNs, although many channel allocation algorithms were proposed, optimal channel assignment should be designed for effective spectrum utilization and maintaining the proposed topology.

In routing layer, the routing protocols designed for ad hoc networks can normally used in WMNs, but design of routing protocols for routing in WMNs is still an active research field. To select a routing path in WMNs, the routing algorithm requires to consider network topology, and the routing path selection is to twist with resource allocation, interference reduction and rate adaptation in multiple hops.

An MR-MC routing protocol not only require to select a path between different nodes [13], but it also require to select the most effective channel or radio node on the path. The routing algorithms should not only enable selection of high-performance links with low end-to-end delay, but also ensure minimum interference between neighbor nodes. Hence, MAC/routing cross-layer design and joint optimization are indispensable for an MR-MC WMN [14].

IV. ISSUES OF WMNS IN TOPOLOGY CONTROL IN MR-MC

The problem of topology control has been studied deeply for wireless ad hoc networks, and there are two books on this topic of TC for wireless ad hoc and sensor networks [15,16]. These books mainly discussed about TC methods for SR-SC wireless ad hoc network. In the book written by Paolo Santi [15], TC is represented as an additional protocol layer between the routing and MAC layer in the protocol stack as shown in Figure 3. The routing layer is required for finding and maintaining the paths between source/destination pairs in the network, and for routing packets toward the destination at the intermediate nodes on the route. Two-way interactions may occur between the routing protocol and TC protocol. The TC protocol, which create and maintains the list of the all immediate neighboring nodes, can send a route update in case it detects that the neigh borers list is considerably changed, and hence leading to a faster response time to topology changes and to decrease packet-lost rate. On the other hand, the routing layer can trigger the re-execution of the TC protocol in case it detects many path breakages in the network.
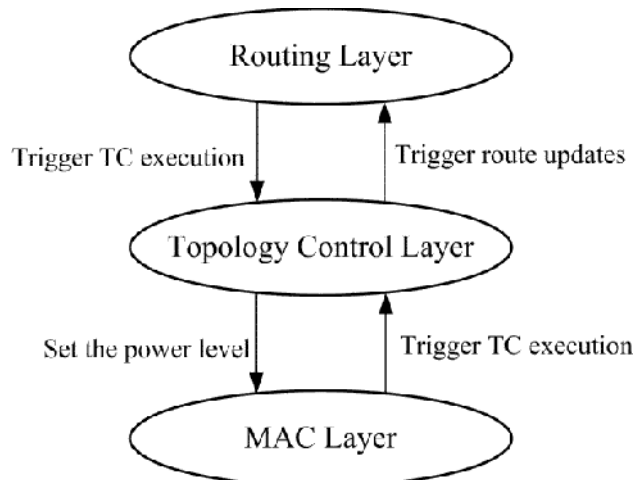

Fig. 3. TC viewed as an additional layer in the protocol stack and interactions with routing and MAC layer.

Furthermore, the author thoughts that the task of setting transmit power levels should be done by the TC layer to take advantage of its network wide perspective. On the other way, the MAC layer can trigger re-execution of the TC protocol in case it discovers any new neigh borer nodes by overhearing the network traffic and analyzing the message headers. The interaction between MAC and TC guarantees a quick response to changes in the network topology.

Existing work on TC in WMNs generally can be categorized to centralized and distributed approaches[16]. The centralized TC approacg have a central server that is responsible for periodically information collection and adaptation. However, the scalability of such kind of approach may be an issue to be addressed. Due to Given large number of nodes (e.g., hundreds of nodes), in conjunction with only a reasonable set of interfaces per node and limited number of channels available in the network, the information of the whole network to be transferred is astronomical. On the other hand, distributed TC algorithms have not based on central server, in which every node controls the topology by using its local information.

The problem of TC has been studied deeply for wireless ad hoc networks [17,18] and power control is the main issue to construct interference optimal topologies through careful tuning of the node transmitting power.

In MR-MC WMN, along with power control (PC), TC is linked with channel assignment (CA) in many ways. In handling the connectivity issue in MR-MC WMNs, the CA decision can actually modifies the network topology, which is a main difference between the SR-MC networks. The problem of TC in MR-MC WMNs has automatically been handled in conjunction with CA [4,19,20]. Hence, both of PC and CA have a direct

impression on the topology of MR-MC WMN. When design TC protocols, it is a challenge to assigning transmitting power levels and orthogonal channels to each interface of nodes effectively with the goal of reducing the effect of interference and maintaining the connectivity of the whole network.

In addition, routing is another important technology that should be taken care on TC mechanisms. In MR-MC WMNs, TC, CA, and routing should be collected together. The network topology of an MR-MC WMN can be modified by the CA decisions. Based on that routing decisions requires to be modified. Thus, routing is directly depends on TC and CA. On the other hand, routing can modifies the traffic load distribution in the network, which is a main factor considered by traffic-aware CA for reduction in the interference dynamically. Accordingly, some collective TC and routing protocols have been proposed recently [10,21,22]. The result of them show that the collective optimization measures increases the performance of the whole network significantly. So, how to jointly optimize TC, CA, and routing is also a main task that must be deal with.

Based on the above discussion, we believes that it is better to view TC as a management functional block in association with the protocol stack in MR-MC WMNs shown in Figure 4. For TC functional block, the inputs, the objective of outputs, and the TC methods are the three characterizing aspects within each category of TC algorithms. A TC method may consider some, if not all, of the given parameters as the inputs.

(i) Node deployment: the geometric position of every node in the network.
(ii) Number of NICs and channels: the number of radios (NICs) at every node and the number of non-overlapping channels assigned to each radio
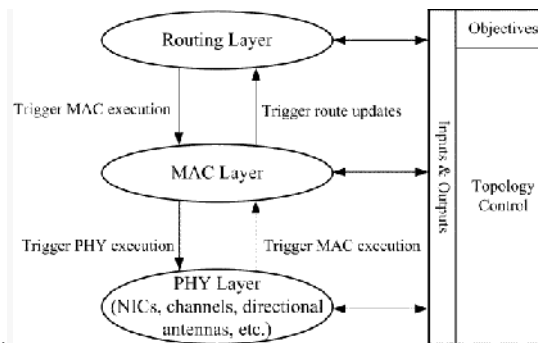

Fig. 4. TC viewed as a management functional block collectively with the protocol layer and interacts with routing layer, MAC and physical layer.

(iii) Power control: power level and maximum power required limit at each node.

(iv) Antenna's type: omnidirectional or directional antenna .

(v) Link and traffic profile: bandwidth of each link and the end-to-end traffic rate of each flow.

(vi) Connectivity and topology constraint: degree of network connectivity and topology type (rooted-tree, graph, hierarchical topologies) to be deployed.

The typical objective of outputs is to maximize the overall performance, while others aim to minimize the overall interference, keep required connectivity, enhance energy efficiency, etc. So TC, PC, CA, and routing are mutually dependent on each other in MR-MC WMNs. The outputs of TC functional block includes all or some TC, PC, CA, and routing packet decisions when they are collectively optimized.

V. REVIEW: MR-MC WMNS TOPOLOGY CONTROL MECHANISMS

In this section, we defines TC mechanisms for MR-MC WMNs in the existing literature. During the discussion, collective dependence of TC on power control, channel allocation, routing decisions and directional antennas in MR-MC WMNs is emphasized. In other way, the described proceures are either directly part of the TC procedure, or act closely to the TC function.

A. Power control (PC)

The main focus of power control (PC) is to choose the transmitting power of every node in such way that the energy consumption is decreased and some properties of the communication graph (eg. connectivity) are maintained. So, PC can be viewed as one way to describe the network connectivity and current physical layer topology. Normally, TC and PC are used interchangeably sometimes in literature because both of them tried to control the transmission range of nodes while trying to are a certain desirable property of the topology. In [23], the difference between them is defined: TC may affect layers upper than PC, by choosing not to make some node adjacencies visible to the network layer (e.g., by filtering at the MAC layer). On the other hand, PC almost in every results has some effect on the topology. Moreover, the goal of PC may not be same as TC but for power conservation etc.

The procedure of PC can be largely classified into static power control and dynamic power control. A static power control allocates power levels to the nodes that do not change frequently over time, unless there are serious changes in the network topology.

On the other way, with dynamic power control strategies, each node changes its power level for transmission frequently over the time. Such kind of changes can be made on basis of per link, per destination, per TDMA slot or on per packet. The Static power control mechanisms are simple and more robust but normally result in suboptimal performance due to their inefficient adaptive nature of changing traffic loads and dynamic wireless conditions. Static power control methods can be further classified into uniform range power control and variable range power control [23].

The problem of power control has been studied deeply for ad-hoc networks and SR-SC WMNs. Few power control strategies proposed for them are still feasible for MR-MC WMNs with aiming at interference reduction and maintaining the connectivity in network. These algorithms for SR-SC WMNs could be classified into two categories: first is centralized control algorithms operated by a central node with more handling capacity and higher energy resources to collect the whole network information; the other is distributed control algorithms controlled by all the nodes with the same configurations, only little local information required. In [24], the author proposed two centralized optimal procedures for creating connected and bi-connected static networks with aiming of minimizing the maximum transmitting power level for every node. A minimum spanning tree based topology control algorithm was described in [25], which achieved network connectivity with minimum power consumption. In [26], a distributed algorithm was proposed for every node to adjust their transmitting power to construct a reliable high-performance topology. In [27],author represented an analytic model to allow every node to adjust its transmitting power for interference reduction and so, achieve better throughput. Jia et al. described a QoS topology control method for ad hoc networks in [28], which developed a network topology that can satisfy end-users' QoS requirements with the minimum total transmission power. In [29], authors systematically studied the connectivity issue in ad hoc networks and developed many approximation algorithms for computing k-connectivity topology using minimum transmission power. Finally, different definitions for interference and many algorithms which targets to develop network topologies such that maximum (or average) link (or node) interference of topology is either minimized or approximately minimized are represented [30].

In [31], the authors describes the problem of topology control by collective power control and routing to maximize the network performance. Two heuristic algorithms are developed to allocate transmission powers to mesh routers, such that total interference or maximum node interference in network is minimized. Simulation results describe the following relationship: topology with minimum total interference has higher overall throughput, while the topology with minimum maximum node interference has higher minimal per-node throughput.

In MR-MC WMNs, for better power transmissions not only enhance interference but also decrease channel reuse in a physical area. Consequently, harsh problems of co-channel and neighboring channel interferences may happen [20]. Thus, efficiency power control strategies are needed to improve the performance of MR-MC WMNs. Many studies have been proposed for multi-channel MAC along with power control [32-35]. The key thoughts include that data packets are transmitted with proper power control to utilize channel reuse, control packets are transmitted with maximal power in order to warn the adjacent nodes of future communication action between the sender and the receiver. In [32,36], power control methods using directional antennas are developed, which makes it possible for dynamic modification of the transmission power for both data and control packets to optimize the energy consumption. The make use of beam-switched antennas allows interference-limited concurrent transmissions. It also provides a node by means of the appropriate tradeoffs between throughput and energy consumption. A dynamic power control method for MR-MC WMNs is developed in [19]. The author proposed a new power choice MR-MC unification protocol (PMMUP) that coordinates local power optimizations at radios of a node. It acts as decentralized aggregate interference prediction process for power optimization in MR-MC WMNs.

B. Assignment of channel

With the use of MR-MC architecture, the capacity of wireless mesh networks can be increased significantly by using multiple channels to reduce the effect of interference and improve the throughput. Effective channel assignment (CA) is required to make sure the optimal use of the limited channels in radio spectrum. CA influence the contention between wireless links and the network topology or connectivity among mesh nodes. In fact, there is a tradeoff between minimizing contention level and maximizing connectivity. The connectivity of WMN should be ensure in the process of assigning channels to the radio nodes. Any change in the CA is to be expected to render some links to be non-existent.

Accordingly, flows that are utilizing these links are disrupted and require to be re-routed, which in turn impacts the network performance. The result of these disruptions can be significant if these changes are frequent. Currently available CA proposals mainly follow two approaches to make sure connectivity. One approach is to allocate a default radio interface on every node configured to a default channel that connects the whole network, and remaining radio interfaces are allocated to non-default channels. This method could ensure connectivity of the whole network by the use of an interface on every node, but it poses heavy overhead on the network. The other approach is to allocate channels to node radio interfaces so that two neighbor nodes forming a link can have a same channel for communication.

As mentioned above, effective CA schemes should take reducing interference into picture. accordingly interference measurement is needed as a crucial criterion of CA. There are two main methods to measure interference. The first is based on topology characteristics, for example by counting number of neighboring nodes using the same channel [37]. The second is based on measuring traffic load carried in neighborhood rather than only the number of neighboring nodes using the same channel [6,20,38]. The former and latter mechanism can be viewed as traffic-independent interference assessment and traffic-aware interference assessment, respectively.

CA protocols can be mainly classified into static, dynamic, and hybrid schemes according to the author in [38,39]. In Static CA there is fixed allocation of channels to the radios nodes which remains unaffected over the course of network operation. Such methods can be further subdivided into common channel allocation and varying channel allocation. Common channel assignment is the simplest scheme, in which radio interfaces of every node are all allocate the same set of channels. The advantage is the maintaining of the connectivity of whole network, and the drawback is the fails to take care for the various factors affecting channel allocation in a WMN. In varying channel assignment, interfaces of different radio nodes may be allocated different sets of channels. Static CA methods are often less adaptive to changing wireless conditions such as external interference and traffic, but such mechanisms are simpler and do not incur channel switching delays.

Dynamic CA allows any interface to be assigned to any channel, and the interfaces can frequently switch from one channel to another taking into account current interference, traffic demand, power allocated. Coordination method is required to ensure nodes which require to communicate are on a same channel.

The advantage of this method is the potential to use some channels with fewer interfaces. The channel switching delays and the requirement for coordination methods for channel switching are the main challenges. Such methods can be further categorized into per link, per packet, per time-slot based methods. These CA methods pose some design problems like multi-channel hidden terminal, sporadic disconnection. On the other way, they have the potential to achieve higher system capacity if designed properly.

When each node in the network modify channels of its radios dynamically, nodes often require more coordination between them to avoid disconnections, deafness problems, and multi-channel hidden terminal problem. Such kind of issues make dynamic CA methods much more complicated.

In hybrid CA schemes, some radios are assigned fixed channels while others switch their channels frequently. These policies take advantages from their partially dynamic design while inheriting simplicity of static methods. Hybrid CA schemes can be further categorized based on whether fixed interfaces use a common channel or dynamic channel approach. Hybrid CA strategies are more attractive because they allow for simple coordination algorithm as fixed CA and keep the flexibility of dynamic CA.

Using multiple radios and multiple channels along centralized CA mechanism in WMN was proposed by Raniwala et al. [6]. In subsequent publications, the authors proposed a dynamic distributed CA and routing mechanism. However, both these schemes based on prior availability of the traffic demands of every mesh node, which is not always feasible. Alicherry et al. [9] proposed a centralized load-awake link scheduling, CA, and routing algorithm. The authors proposes division of fixed duration time frames into slots where a particular set of nodes can transmit within each time slot on particular channels allocated by a CA algorithm. The centralized nature of the proposed mechanism and the thinking of infrequent modifications in traffic demands makes proposed solution less effective. The hybrid multiple channel protocol (HMCP) defined in [5] requires radio nodes to switch between channels on per-packet basis, which needs time synchronization and coordination between mesh nodes. Breadth first search-channel assignment (BFS-CA) method proposed in [20] needs certain number of Mesh Routers along with certain number of radio interfaces to be positioned at certain hops from gateway, which could ensure connectivity of the whole network. Main disadvantage of BFS-CA algorithm is that one non-overlapping channel along with one radio of the mesh router is always reserved for default channel, which does not make effective utilization of available interfaces and

channels. In [40], a cluster-based multipath topology control and channel allocation scheme (CoMTaC) is proposed. It explicitly creates a isolation between the CA and TC functions, aims at minimizing flow disruptions. A cluster-based method is employed to make sure basic network connectivity in [40]. CoMTaC also takes advantages of the inherent multiple paths that exist in typical WMN by developing a spanner of the network graph and using additional node interfaces. The second phase of CoMTaC presents a dynamic distributed CA algorithm, which applies a novel interference estimation method based on the average link-layer queue length within interference domain. partly overlapping channels are also integrated in the CA process to improve the network capacity. The experimental results shows that the proposed method outperforms existing dynamic channel assignment schemes by a minimum of factor of 2.

In [41], a CA mechanism termed as topology-controlled interference-aware channel-assignment algorithm (TICA) was developed to use TC based PC for CA in MR-MC WMNs. In [37], the author considered the CA problem in multi-radio WMN that involves allocate channels to radio interfaces for achieving effective channel utilization. A graph-theoretic formulation of CA guided by a novel TC perspective is proposed, and the resulting optimization problem is NP-complete. Then, it proposes an ILP (Integer Linear Program) formulation that is used for obtaining lower bound for the optimum, and develops new greedy heuristic CA algorithm (termed CLICA) for searching connected, low interference topologies by utilizing multiple channels. Their evaluations shows that the proposed CLICA mechanism exhibits same behavior and comparable performance relative to optimum bound with respect to interference and capacity measures. Additionally, their extensive simulation studies shows that it provides a large interference reduction even with small number of radios per node, which in turn results to significant gains in both link layer and multi-hop efficiency in 802.11-based multi-radio mesh networks.

In [42], the synergy between TC and CA is broken to reduce the overall interference in MR-MC WMNs. It presents CA as a non-cooperative game, with nodes selecting less interference channels while maintains some degree of network connectivity. This game is shown to be a effective game, which ensure the existence of, and unions to, a Nash equilibrium (NE). Further, the performance of NE topologies with respect to interferences and connectivity objective is evaluated. By quantifying the effect of channel availability on interference efficiency, it illuminates the exchange between interference reduction that can be reached by

distributing interference over multiple channels and the cost of having some additional channels. Finally, it studies spectral occupancy of steady state topology, and shows that even with non-cooperative behavior, the NE topologies reached load balancing. To maximal network utilization and minimal traffic disruption, a polynomially bound online heuristic approach, DeSARA, is presented in [43], which finds CA for the current traffic demand by considering existing CA of the network to minimize the reconfiguration overhead. In [44], authors defines a utility-based framework for joint CA and TC in MR-MC WMNs, and represents a greedy algorithm for solving the corresponding optimization problem. Main features of the proposed algorithm are the support for different targeted objectives and the effective utilization of wired network gateways. Si et al. conducted an detail survey of the CA algorithm for MR-MC WMNs in the literature [45]. In this survey, different CA approaches are examined individually with their benefits' and limitations are highlighted, and categorical and overall comparisons for them are also given in compete detail.

C. Routing

As we mentioned earlier, TC, CA, PC, and routing are integrated together in MR-MC WMNs. On one hand, CA and PC finds the connectivity between nodes since two nodes can communicate with each other only when they are on same channel and within transmission range of each other. As we know, routing decisions are mainly based on the network topology. Thus, CA and PC have directly effects routing. On the other hand, channel and transmission power should be dynamically modified according to the current traffic status, which is defined by routing algorithm. So, routing, CA, and PC should be jointly optimized for MR-MC WMNs.

In [21], the authors proposed a joint topology control and routing (JTCR) protocol for MR-MC networks to make use of both channel diversity and spatial reusability, which addressed collective topology control and routing problem in an IEEE 802.11-based MR-MC wireless mesh networks. An Equivalent Channel Air Time Metric (ECA TM) was developed to quantify the difference of various adjustment candidates. The main part of this protocol is to select a feasible adjustment candidate with smallest metric value and then to coordinate the affected nodes through negotiation to understand the adjustment.

Tang et al. examined interference-aware TC and QoS routing in multi-channel wireless mesh networks based on IEEE 802.11 with dynamic traffic [46]. They described a original definition of co-channel interference to accurately capture the influence of the interference. According to definition, they defined and presents an effective heuristic for the minimal interference survivable topology control (INSTC) problem which seek a channel allocation for the given network such that the induced network topology is interference-minimal among all *K*-connected topologies. Then, they described the bandwidth-aware routing (BAR) problem for a given network topology, which finds routes for QoS connection requests along with bandwidth needs. A polynomial time optimal algorithm to solve the BAR problem is defined under the assumption that traffic demands are splittable. For non-splittable case, they present a maximal bottleneck capacity path routing heuristic. Simulation results shows that compared with the simple common channel allocation and shortest path routing approach, their method improves the system performance by 57 % on average cases in terms of connection blocking ratio.

In [10], the authors defined the TiMesh MC-WMN architecture, in which logical channel assignment, topology design, interface allocation and routing are formulated as a integrated linear mixed integer optimization problem. The formulated model takes care number of available NICs in routers, number of available orthogonal frequency channels, estimated traffic load between different source and destination pairs and effective capacity of the logical links. The developed method balances the load among logical links and provides better effective capacity for the bottleneck links.

All the above studies assumes channels with fixed, pre-determined width, which is direct result of static spectrum separation style of existing wireless technologies. In [22], authors presents a integrated channel width adaptation, topology control and routing mechanism for MR-MC WMNs. The authors mathematically formulates the channel width adaptation, topology control and routing as a collective mixed 0–1 integer linear optimization scheme. This model formulation explore the use of channels through dynamic bandwidth adaptation. It does not treat the spectrum as set of discrete orthogonal channels but the continuous blocks, and exploit partially overlapped channels along with variable widths to further increase the spectrum efficiency. The advantage of channel width adaptation are two folds. On one way, the load can be distributed as evenly as possible through the spectrum in a fine granularity to reach channel load balance. On the other way, in a scenario with many interfering links, by creating extra small-width orthogonal channels, contention and confliction can be decreased.

D. TC with directional antennas

Directional antennas is another main technology proposed as one of the viable means to increase the performance of WMNs including enhance capacity, and range of communications, reduce the interference, conserve the energy and resolving collisions [47].

In MR-MC WMNs, interference among transmissions operating on same frequency channel is alleviated by using multiple radios on every mesh node and by allocating different channels to each radio, thus enable more concurrent transmissions than single radio single channel WMNs. Though more simultaneous transmissions are acceptable in MR-MC WMNs, interference cannot be eliminated completely due to restricted number of available non-overlapping channels and broadcasting nature of wireless medium [48]. With use of directional antennas in MR-MC WMN has been recognized as an convenience solution to the interference problem. The basic reason is that directional antenna can focus energy in intended direction instead of spreading it out in all directions, thus enhance spatial reuse. Networks using directional antennas allow more parallel transmissions than those which are using conventional omnidirectional antennas with the same number of available non-overlapping channels, allow nodes to communicate on same-time without interference, and establish links between nodes far away from each other, and the number of routing hops can be lower than that of omnidirectional antennas.

Antenna orientation affects the throughput of MR-MC WMNs along with PC, CA and routing strategies. Antenna orientation effects the network topology, thus affects channel allocation and routing strategies. Therefore, proper modeling methods are needed in designing MR-MC WMNs with directional antennas.

An MR-MC WMN using multiple directional antennas is described in [49]. This study performs theoretical analysis and presents theoretical bounds on capacity for MR-MC WMN with directional antenna. DMesh [50] is a wireless mesh network architecture that incorporate directional antennas in MR-MC WMNs. DMesh assume perfect antenna orientation between communicating node pairs. This may not be optimum orientation to improve interference. DMesh dedicates an seprate NIC for a wireless link and thus does not utilize network resources effectively. It also improves the connectivity and results in longer routing paths, hence more interference. In [48], authors proposed an mechanism to produce joint decisions on routing and channel allocation with practical implementation considerations for MR-MC WMNs with switched beam

antennas which needs switching and synchronization. They don't take into account the directional interface assignment issue, the antennas are assumed to points to each other during communication. The authors in [51] defined the antenna orientation using a sectored connectivity graph and formulated their architecture mathematically as a combined integer linear problem. The problem is then solved to obtain topology, channel allocation, interface allocation and routing paths. In [52], Liu *et al.* proposed topology control mechanism for MR-MC WMNs with directional antennas. The developed three-step solution starts by constructing a set of routing trees and seek to balance the traffic among tree links. In the second step, it performs interface allocation for each node in the tree with the objective of balancing traffic load among the links served by every node. Finally, it performs channel allocation and antenna orientation to minimal interference while covering all the intended neighbors of the node. Based on the method developed in [52], the authors in [53] presented an enhanced version of topology control mechanism. In [53], the routing tree construction method is improved in the first step of the solution in [52].

VI. CONCLUSIONS

With the growth demand of deployment and advancement of wireless technologies, the MR-MC WMN has been started to be adopted as a attractive solution. To make use of its advantages on improved network performance, new design and operation challenges requires to be deal with. With such networking architecture, it results that many network operations like topology control, power control, channel allocation and routing, are integrated together. We argue that it is better to view TC as management functional block in association with protocol layers in MR-MC WMNs. In survey, this methodology is demonstrated by so many published studies with collective optimization of some or all functions of topology control, power control, channel allocation, and routing decisions. It requires to point out that such joint optimization procedure often leads to NP-hard complexity and hence suboptimal heuristic procedure with reduced complexity have been investigated. Considering all envisage applications, MR-MC WMNs appears to have unprecedented and so far unrealized potentials. With latest and future research efforts, a unified framework integrating all mutual dependent functions is more required for MR-MC WMNs. We are expecting to see further expansion of this subject with such methodology.

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