Liu and Bai *EURASIP Journal on Wireless Communications and Networking* 2012, **2012**:324
http://jwcn.eurasipjournals.com/content/2012/1/324

EURASIP Journal on
Wireless Communications and Networking
a SpringerOpen Journal

REVIEW **Open Access**

An overview of topology control mechanisms in multi-radio multi-channel wireless mesh networks

Fang Liu[1] and Yong Bai[2*]

Abstract

Wireless mesh network (WMN) is a key technology for supporting a variety of application scenarios. Recently, it evolves toward a multi-radio multi-channel (MR-MC) WMN architecture, which can improve network performance by equipping each node with multiple radio interfaces and by using multiple non-overlapping channels. This evolution poses new challenges on network design. Specifically, topology control (TC), one of the fundamental research topics in WMNs, has also received extensive attention in MR-MC WMNs. This article presents an overview of TC mechanisms in the existing literature with emphasis on the mutual dependence of TC on other networking issues such as power control, channel assignment, routing, and directional antennas.

Introduction

Wireless mesh networks (WMNs), with multiple hops and mesh topology, has been evolved as a key technology for a variety of application scenarios including broadband home networking, community and neighborhood networking, enterprize networking, and metropolitan area networking [1]. As illustrated in Figure 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 or others). Mesh clients connect to mesh routers using a wireless or a wired link. Every mesh router performs relaying of data for other mesh routers, and certain mesh routers also have additional capability of being Internet gateways. Such gateway routers often have a wired link which carries the traffic between the mesh routers and the Internet.

The WMNs have attractive advantages such as self-organization, self-healing, self-configuration, enabling quick deployment, easy maintenance, and cost effectiveness. The WMNs inherit almost all characteristics of more general wireless ad hoc networks (e.g., decentralized design, distributed communications). Nevertheless, unlike the mobility of ad hoc nodes, mesh routers are usually fixed. Therefore, ad hoc networks are often energy-constrained, and energy efficiency is an important design target. On the other hand, mesh routers have no limitations regarding energy consumption.

Traditional WMNs operate in single-radio single-channel (SR-SC) architecture where each mesh router has only one network interface card (NIC) and all the mesh routers share one common radio channel. In such a networking scenario, the network suffers from low throughput and capacity due to packet collisions and frequent backoffs, especially for real-time applications such as VoIP transmission across multihop WMNs [2,3]. In fact, the IEEE 802.11b/g bands and the IEEE 802.11a band provide 3 and 12 non-overlapping frequency channels, respectively. Though there exists significant interference between these standard non-overlapping channels in the current commodity IEEE 802.11 hardware, this problem can be resolved by using better frequency filters in hardware for multi-channel use. Hence, the use of single-radio multiple-channels (SR-MC) has been proposed to elevate the performance of WMNs [4,5]. Compared with the SR-SC architecture, the SR-MC architecture can help to alleviate the interference and increase network throughput. A required function of the SR-MC solutions is for each router to dynamically switch between channels with

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*Correspondence: bai@hainu.edu.cn
[2]College of Information Science & Technology, Hainan University, Haikou, Hainan 570228, China
Full list of author information is available at the end of the article

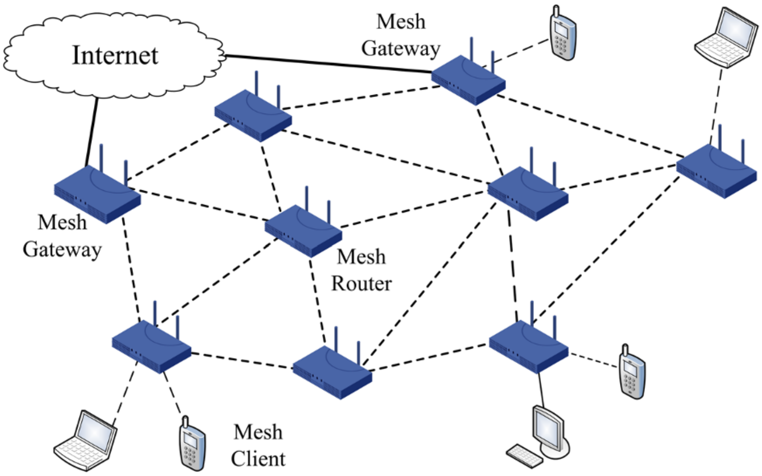

Figure 1 Wireless mesh network architecture with mesh gateway, mesh routers, and mesh clients.

dynamic network traffic, while coordinating with neighboring nodes to ensure communication over a common channel for some period. However, such coordination is usually based on tight time synchronization among nodes, which is difficult to realize in a multihop WMN. Moreover, fast channel switching capability (in the order of 100 μs) is not yet available with commodity hardware. It is reported 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 effective solution to overcome high latency and at the same time improve throughput of WMN would be using a Multi-Radio Multi-Channel (MR-MC) architecture. In such a solution, each mesh router is equipped with multiple NICs and each NIC can operate on multiple frequency channels. With MR-MC architecture, multiple transmissions/receptions can happen concurrently, and neighboring links assigned to different channels can carry traffic free of interference. However, the use of MR-MC architecture poses various new issues. In general, these issues include topology control, power control, channel assignment, link scheduling, and routing. Among them, the issue of topology control (TC) has received extensive attention. TC is one of the fundamental research topics in WMNs. When designed properly, it can help to improve the operation of WMNs on connectivity, energy efficiency, mobility resilience, network capacity increase, interference reduction, etc. In MR-MC WMNs, TC is mutually dependent on power control, channel assignment, and routing, which poses new design challenges on its design.

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

Multi-radio multi-channel (MR-MC) WMNS

In MR-MC WMNs, each mesh router is equipped with multiple NICs and each NIC can operate on multiple frequency channels. In the experimental MC-WMN testbeds in [6,8], each mesh router is equipped with two NICs. Providing 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 per router, and five frequency channels. The label number indicates the assigned channels that are reused spatially.

The MR-MC solution has attracted a lot of attention with the benefits of interference reduction and network scalability improvement in wireless mesh networks. Nevertheless, the MR-MC model also poses technical issues to be dealt with [10]. As mentioned before, the number of available channels is limited to 3 or 12 within the IEEE 802.11 frequency bands. This implies that some logical links may be assigned the same channel. In this case, interference occurs if these logical links are close to each other, and hence the interfering links cannot be active simultaneously. Furthermore, the number of available NICs is also limited, and hence some logical links in a router need to share a NIC to transmit and receive the data packets. When two logical links in a router share a NIC, they are required to operate over the same frequency channel,

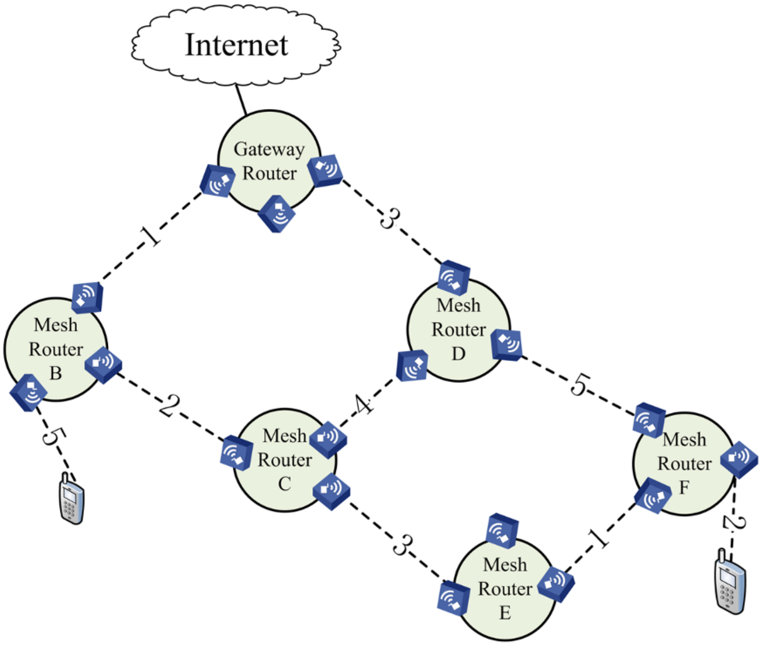

Figure 2 Example of an MR-MC WMN (six wireless mesh routers, five frequency channels, and three NICs per mesh router).

and cannot be active simultaneously. Thus, it significantly reduces their effective capacity. The effective link capacity can be increased by removing some of the links from the logical topology. However, when some of the links are not activated, the number of hops through some routing paths may be increased, and the logical topology may not even be connected. Therefore, how many logical links should be assigned between neighboring routers, how to allocate interfaces and channels, and through which logical links should the packets be forwarded need to be considered in MR-MC WMNs.

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

Considering the above issues with the MR-MC architecture, existing communication protocols, ranging from routing, MAC, and physical layers, need to be revisited and enhanced.

In physical layer, techniques mainly focus on three research directions: increasing transmission rate, improving error resilience capability, and enhancing reconfigurability and software controllability of radios [11]. In order to increase the capacity of wireless networks, various high-speed physical techniques, such as OFDM, UWB, and MIMO, have been invented. To improve error resilience, many channel coding schemes have been developed, and adaptive channel coding schemes and cognitive radios are considered to utilize the wireless spectrum much efficiently. In MR-MC WMNs, the cost of wireless radios with multiple transceivers is still very high, thus it is necessary to optimize the hardware design so as to reduce the cost. Moreover, directional antennas have been considered to be used for MR-MC systems. Besides these, power control is another interesting aspect that should be thoroughly investigated, since assigning optimal power for controlling the topology can reduce interference and in turn help improving overall network performance.

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

In routing layer, the routing protocols developed for ad hoc networks can usually be applied to WMNs, but the design of routing protocols for WMNs is still an active research area. To select a routing path in WMNs, the routing algorithm needs to consider network topology, and the routing path selection is intertwined with resource allocation, interference avoidance and rate adaptation across multiple hops. An MR-MC routing protocol not only needs to select a path in between different nodes [13], but it also needs to select the most appropriate channel or radio on the path. The routing algorithms should not only enable selection of high-throughput links with low end-to-end delay, but also ensure minimal interference between neighboring nodes. Hence, MAC/routing cross-layer design and joint optimization are indispensable for an MR-MC WMN [14].

Challenges on topology control in MR-MC WMNS

The problem of TC has been studied extensively for wireless ad hoc networks, and there are two books dedicated for the subject of TC for wireless ad hoc and sensor networks [15,16]. These two books mainly talk about TC mechanisms for SR-SC wireless ad hoc network. In the book written by Paolo Santi [15], TC is viewed as an additional protocol layer positioned between the routing and MAC layer in the protocol stack as shown in Figure 3. The routing layer is responsible for finding and maintaining the routes between source/destination pairs in the network, and for forwarding packets toward the destination at the intermediate nodes on the route. Two-way interactions may happen between the routing protocol and TC protocol. The TC protocol, which creates and maintains the list of the immediate neighbors of a node, can trigger a route update in case it detects that the neighbor list is considerably changed, and hence lead to a faster response time to topology changes and to a reduced packet-loss rate. On the other hand, the routing layer can trigger the reexecution of the TC protocol in case it detects many route breakages in the network. Furthermore, the author believes the task of setting transmit power levels should be performed by the TC layer to take advantage of its networkwide perspective. On the other hand, the MAC layer can trigger reexecution of the TC protocol in case it discovers new neighbor nodes by overhearing the network traffic and analyzing the message headers. The interactions between MAC and TC ensure a quick response to changes in the network topology.

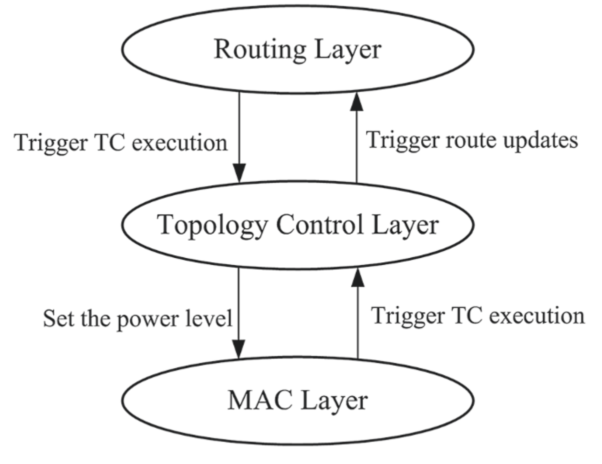

Figure 3 **TC viewed as an additional layer in the protocol stack and interactions with routing and MAC layer.**

Existing works on TC in WMNs generally can be classified to centralized and distributed approaches [16]. The centralized TC algorithms have a central server that performs periodically information collection and adaptation. However, the scalability of such approach may be an issue. Given large number of nodes (e.g., hundreds of nodes), in conjunction with even only a reasonable set of interfaces per node and limited number of channels in the network, the information of the entire network to be transferred is astronomical. Correspondingly, distributed TC algorithms have no use of the central server, in which each node controls the topology by using local information.

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

In MR-MC WMN, besides power control (PC), TC is interlinked with channel assignment (CA) in many ways. In addressing the connectivity issue in MR-MC WMNs, the CA decisions can actually change the network topology, which is a key difference between the SR-MC networks. The problem of TC in MR-MC WMNs has implicitly been addressed in conjunction with CA [4,19,20]. Hence, both of PC and CA have a direct impact on the topology of MR-MC WMN. When design TC mechanisms, it is a challenge to allocate transmitting power levels and orthogonal channels to every interface of nodes efficiently with the purpose of reducing the effect of interference and maintaining the connectivity of the entire network.

In addition, routing is another key technology that should be taken into account on TC mechanisms. In MR-MC WMNs, TC, CA, and routing might be coupled together. The network topology of an MR-MC WMN can be changed by the CA decisions. Accordingly, the routing decisions need to be updated. Thus, routing is dependent on TC and CA. On the other hand, routing can change the traffic load distribution in the network, which is a primary factor considered by traffic-aware CA to reduce the interference dynamically. Actually, some joint TC and routing protocols have been proposed recently [10,21,22]. The results of them show that the joint optimization measures enhance the performance of the entire network significantly. Thus, how to jointly optimize TC, CA, and routing is also a challenge that must be dealt with.

Based on the above discussion, we believe that it is better to view TC as a management functional block in connection with the protocol stack in MR-MC WMNs shown in Figure 4. For the TC functional block, the inputs, the objectives of outputs, and the TC methods (techiniques) are the three characterizing aspects within each category of TC algorithms. A TC mechanism may 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 NICs and channels: the number of radios (NICs) at each node and the number of non-overlapping channels available at each radio.
- Power profile: power level and maximum power limit at each node.
- Type of antenna: omnidirectional or directional antenna pattern at each node.
- Link and traffic profile: the bandwidth of each link and the end-to-end traffic rate of each flow.
- Connectivity and topology constraint: the level of network connectivity and type of topology (rooted-tree, graph, hierarchical topologies) to be achieved.

The typical objective of outputs is to maximize the overall throughput, while others aim to minimize the overall interference, keep required connectivity, improve energy efficiency, etc. Since TC, PC, CA, and routing are mutually dependent in MR-MC WMNs. The outputs of TC functional block may include all (or some) TC, PC, CA, and routing decisions when they are jointly optimized.

Review: Topology control mechanisms for MR-MC WMNS

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

Power control

The key of power control (PC) is to choose the transmitting power of each node in such a way that energy consumption is reduced and some properties of the communication graph (typically, connectivity) are maintained. Hence, PC can be viewed as one means to determine the network connectivity and underlying physical layer topology. Actually, TC and PC are used interchangeably sometimes in literature since both of them attempt to control the transmission range of nodes while trying to achieve a certain desirable property of the topology. In [23], the distinction between them is identified: TC may affect layers higher than PC, by choosing not to make certain node adjacencies visible to the network layer (e.g., by filtering at the MAC layer). On the other hand, PC almost invariably results in some effect on the topology. Moreover, the objective of PC may not be same as TC but for power conservation, etc.

The mechanisms of PC can be largely classified into static power control and dynamic power control. A static power control allocation assigns power levels to the nodes that do not change frequently over time, unless there are drastic changes in the network topology. On the other hand, with dynamic power control strategies, every node

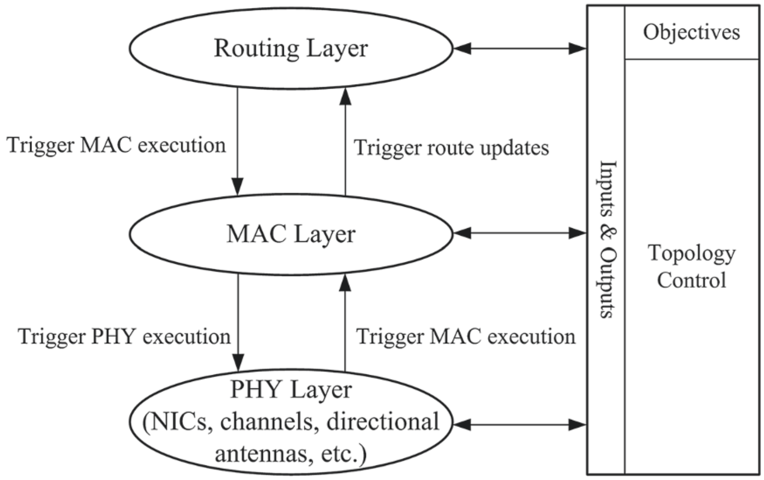

Figure 4 **TC viewed as a management functional block joint with the protocol layers and interactions with routing, MAC, and physical layers.**

changes its power level for transmission frequently over the time. Such changes can be made on per link, per destination, per TDMA slot or per packet basis. The Static power control mechanisms are simpler and more robust but often result in suboptimal performance due to their inefficient adaptation of changing traffic demands and dynamic wireless conditions. Static power control mechanisms can be further classified into uniform range power control and variable range power control [23].

The problem of power control has been studied extensively for ad-hoc networks and SR-SC WMNs. Some power control strategies proposed for them are still appropriate for MR-MC WMNs with the purpose of reducing interference and maintaining the connectivity. These algorithms for SR-SC WMNs could be divided into two categories: one is centralized control algorithms operated by a central node with higher handling capacity and more energy resources to collect the entire network information; the other is distributed control algorithms run by all the nodes with the same configurations, only local information required. In [24], the author proposed two centralized optimal algorithms for creating connected and bi-connected static networks with the objective of minimizing the maximum transmitting power for each node. A minimum spanning tree based topology control algorithm was proposed in [25], which achieved network connectivity with minimal power consumption. In [26], a distributed algorithm was developed for each node to adjust its transmitting power to construct a reliable high-throughput topology. In [27], Hou et al. presented an analytic model to allow each node to adjust its transmitting power to reduce interference and hence achieve high throughput. Jia et al. proposed a QoS topology control mechanism for ad hoc networks in [28], which constructs a network topology that can meet end-users' QoS requirements with the minimal total transmission power. In [29], the authors systematically studied the connectivity issue in ad hoc networks and proposed several approximation algorithms for computing k-connectivity topology using minimal transmission power. Finally, different definitions of interference and several algorithms which target to construct network topologies such that maximum (or average) link (or node) interference of the topology is either minimized or approximately minimized are presented [30]. In [31], the authors consider the problem of topology control by joint power control and routing to maximize the network throughput. Two heuristic algorithms are designed to assign transmission powers to mesh routers, such that the total interference or the maximum node interference in the network is minimized. Simulation results reveal the following relationship: the topology with minimum total interference has higher total throughput, while the topology with minimum maximal node interference has higher minimal per-node throughput.

In MR-MC WMNs, high power transmissions not only increase interference but also degrade channel reuse in a physical area. Consequently, severe problems of co-channel and adjacent channel interferences may occur [20]. Thus, efficiency power control strategies are required to enhance the performance of MR-MC WMNs. Numerous studies have been proposed for multi-channel MAC with power control [32-35]. The key ideas include that data packets are transmitted with proper power control to exploit channel reuse, control packets are transmitted with maximum power in order to warn the neighboring nodes of future communication activity between the sender and the receiver. In [32,36], power control approaches using directional antennas are proposed, which makes it possible for dynamic adjustment of the transmission power for both data and control packets to optimize energy consumption. The use of beam-switched antennas permits interference-limited concurrent transmissions. It also provides a node with the appropriate tradeoffs between throughput and energy consumption. A dynamic power control for MR-MC WMNs is proposed in [19]. The author proposed a new power selection MR-MC unification protocol (PMMUP) that coordinates local power optimizations at the radios of a node. It acts as a decentralized aggregate interference prediction method for power optimization in MR-MC WMNs.

Channel assignment

With the MR-MC architecture in use, the capacity of wireless mesh networks can be improved significantly by using multiple channels to reduce the effect of interference and enhance the throughput. Efficient channel assignment (CA) is required to ensure the optimal use of the limited channels in the radio spectrum. CA influences the contention among wireless links and the network topology or connectivity between mesh nodes. In fact, there is a tradeoff between minimizing the level of contention and maximizing connectivity. The connectivity of WMN should be ensured in the process of assigning channels to the radios. Any change in the CA is likely to render certain links to be non-existent. Consequently, flows that are utilizing these links are disrupted and need to be re-routed, which in turn impacts the network throughput. The effect of these disruptions can be significant if these changes are frequent. Existing CA proposals mainly follow two approaches to ensure connectivity. One approach is to assign a default radio interface on each node configured to a default channel that connects the entire network, and remaining radio interfaces are assigned to non-default channels. This approach could ensure connectivity of the entire network by the use of an interface on each node, but it imposes heavy overhead on the network. The other approach is to assign channels to node radio interfaces such that two neighbor nodes forming a link can have a common channel for communication.

As mentioned above, efficient CA schemes should take reducing interference into account. Consequently, interference measurement is required as a crucial criterion of CA. There are two major methods to measure interference. The first one is based on topological characteristics, for example by counting number of neighbors using the same channel [37]. The second one operates by measuring traffic load carried in the neighborhood rather than only the number of neighbors using the same channel [6,20,38]. The former and the latter approaches can be viewed as traffic-independent interference estimation and traffic-aware interference estimation, respectively.

CA protocols can be broadly classified into static, dynamic, and hybrid schemes according to the description in [38,39]. Static CA is a fixed assignment of channels to the radios of nodes which remains unchanged over the course of network operation. Such schemes can be further subdivided into common channel assignment and varying channel assignment. Common channel assignment is the simplest scheme, in which the radio interfaces of each node are all assigned the same set of channels. The benefit is the maintaining of the connectivity of network, and the drawback is the failure to account for the various factors affecting channel assignment in a WMN. In varying channel assignment, interfaces of different nodes may be assigned different sets of channels. Static CA mechanisms 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 any channel, and the interfaces can frequently switch from one channel to another considering current interference, traffic demands, power allocation. Coordination mechanism is needed to ensure nodes which need to communicate are on a common channel. The benefit of this scheme is the potential to use many channels with fewer interfaces. The channel switching delays and the need for coordination mechanisms for channel switching are the key challenges. Such mechanisms can be further classified into per link, per packet, per time-slot based mechanisms. These CA policies pose novel design problems like multi-channel hidden terminal, sporadic disconnections. On the other hand, they have the potential to achieve better system capacity if designed properly.

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

In hybrid CA schemes, some of the radios are assigned fixed channels while others switch their channels dynamically. These policies benefit from their partially dynamic design while inheriting simplicity of static mechanisms. Hybrid CA schemes can be further classified based on whether the fixed interfaces use a common channel or varying channel approach. Hybrid CA strategies are attractive because they allow for simple coordination algorithms as fixed CA and retain the flexibility of dynamic CA.

Using multiple radios and multiple channels with a centralized CA scheme in WMN was proposed by Raniwala et al. [6]. In a subsequent publication, the authors proposed a dynamic distributed CA and routing algorithm. However, both these schemes rely on prior availability of the traffic demands of each mesh node, which is not always feasible. Alicherry et al. [9] proposed a centralized load-aware link scheduling, CA, and routing protocol. The authors propose the division of fixed duration time frames into slots where a specific set of nodes can transmit within each time slot on specific channels assigned by a CA algorithm. The centralized nature of the proposed algorithm and the assumption of infrequent changes in traffic demands make the proposed solution less attractive. The hybrid multiple channel protocol (HMCP) proposed in [5] requires radios to switch between channels on a per-packet basis, which requires time synchronization and coordination between mesh nodes. The breadth first search-channel assignment (BFS-CA) scheme proposed in [20] requires certain number of Mesh Routers with certain number of radio interfaces to be placed at certain hops from the gateway, which could ensure connectivity of the entire network. The drawback of BFS-CA algorithm is that one non-overlapping channel and one radio of the mesh router is always reserved for default channel, which does not make efficient utilization of available interfaces and channels. In [40], a cluster-based multipath topology control and channel assignment scheme (CoMTaC) is presented. It explicitly creates a separation between the CA and TC functions, thus minimizing flow disruptions. A cluster-based approach is employed to ensure basic network connectivity in [40]. CoMTaC also takes advantage of the inherent multiple paths that exist in a typical WMN by constructing a spanner of the network graph and using the additional node interfaces. The second phase of CoMTaC proposes a dynamic distributed CA algorithm, which employs a novel interference estimation mechanism based on the average link-layer queue length within the interference domain. Partially overlapping channels are also included in the CA process to enhance the network capacity. The experimental results show that the proposed scheme outperforms existing dynamic channel assignment schemes by a minimum of a factor of 2.

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

In [42], the synergy between TC and CA is exploited to reduce the overall interference in MR-MC WMNs. It formulates CA as a non-cooperative game, with nodes selecting low interference channels while maintaining some degree of network connectivity. This game is shown to be a potential game, which ensures the existence of, and convergence to, a Nash equilibrium (NE). Next, the performance of NE topologies with respect to interference and connectivity objectives is evaluated. By quantifying the impact of channel availability on interference performance, it illuminates the tradeoff between interference reduction that can be achieved by distributing interference over multiple channels and the cost of having additional channels. Finally, it studies the spectral occupancy of steady state topologies, and shows that despite the non-cooperative behavior, the NE topologies achieve load balancing. To maximize network utilization and minimizing traffic disruption, a polynomially bound online heuristic algorithm, DeSARA, is proposed in [43], which finds the CA for the current traffic demand by considering the existing CA of the network to minimize the reconfiguration overhead. In [44], the authors define a utility-based framework for joint CA and TC in MR-MC WMNs, and present a greedy algorithm for solving the corresponding optimization problem. Key features of the proposed approach are the support for different target objectives and the efficient utilization of wired network gateways. Si et al. conducted an in-depth survey of the CA approaches for MR-MC WMNs in the literature [45]. In the survey, different CA approaches are examined individually with their advantages and limitations highlighted, and categorical and overall comparisons for them are also given in detail.

Routing

As we mentioned, TC, CA, PC, and routing are coupled together in MR-MC WMNs. On one hand, CA and PC determine the connectivity between nodes since two nodes can communicate with each other only when they are on a common channel and within the transmission range of each other. As we know, routing decisions are largely made based on the network topology. Thus, CA and PC have direct impacts on routing. On the other hand, channel and transmission power should be dynamically adjusted according to the traffic status, which is determined by routing algorithm. Therefore, routing, CA, and PC should be jointly optimized for MR-MC WMNs.

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

Tang et al. studied interference-aware TC and QoS routing in IEEE 802.11-based multi-channel wireless mesh networks with dynamic traffic [46]. They presented a novel definition of co-channel interference to precisely capture the influence of the interference. According to this definition, they formally defined and presented an effective heuristic for the minimum interference survivable topology control (INSTC) problem which seeks a channel assignment for the given network such that the induced network topology is interference-minimum among all K-connected topologies. Then, they formulated the bandwidth-aware routing (BAR) problem for a given network topology, which seeks routes for QoS connection requests with bandwidth requirements. A polynomial time optimal algorithm to solve the BAR problem is presented under the assumption that traffic demands are splittable. For the non-splittable case, they present a maximum bottleneck capacity path routing heuristic. Simulation results show that compared with the simple common channel assignment and shortest path routing approach, their scheme improves the system performance by 57 % on average in terms of connection blocking ratio.

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

All the above studies assume channels with fixed, predetermined width, which is the direct result of the static spectrum partition style of existing wireless technologies. In [22], the authors proposed a joint channel width adaptation, topology control and routing protocol for MR-MC wireless mesh networks. The authors mathematically formulated the channel width adaptation, topology control and routing as a joint mixed 0–1 integer linear optimization problem. This model formulation explored the use of channels with dynamic bandwidth adaptation. It does not treat the spectrum as the set of discrete orthogonal channels but the continuous blocks, and exploits partially overlapped channels with variable widths to further improve the spectrum efficiency. The advantages of channel width adaptation are two folds. On one hand, the load can be distributed as evenly as possible across the spectrum in a fine granularity to achieve channel load balance. On the other hand, in a scenario with many interfering links, by creating more small-width orthogonal channels, contention and confliction can be reduced.

TC with directional antennas

Directional antennas is another key technology proposed as one of the viable means to enhance the performance of WMNs including increasing capacity, and range of communications, reducing the interference, conserving energy and resolving collisions [47].

In MR-MC WMNs, the interference among transmissions operating on the same frequency channel is alleviated by using multiple radios on each mesh node and by assigning different channels to each radio, thus enabling more concurrent transmissions, compared with the single radio single channel WMNs. Although more simultaneous transmissions are allowed in MR-MC WMNs, the interference cannot be eliminated completely due to limited number of available non-overlapping channels and broadcast nature of the wireless medium [48]. Using directional antennas in MR-MC WMN has been recognized as an attractive solution to the interference problem. The main reason is that directional antenna can focus energy in the intended direction instead of spreading it out on all directions, thus improves spatial reuse. Networks using directional antennas typically allow more parallel transmissions than those using conventional omnidirectional antennas with the same number of available non-overlapping channels, allow nodes to communicate simultaneously without interference, and potentially establish links between nodes far away from each other, and the number of routing hops can be fewer than that of omnidirectional antennas.

Antenna orientation affects the performance of MR-MC WMNs as well as PC, CA and routing strategies. Antenna orientation has an impact on network topology, thus affects channel assignment and routing strategies. Therefore, proper modeling schemes are required in designing MR-MC WMNs with directional antennas.

An MR-MC WMN using multiple directional antennas is proposed in [49]. This study performs theoretical analysis and presented theoretical bounds on the capacity for MR-MC wireless networks with directional antenna. DMesh [50] is a wireless mesh network architecture that incorporates directional antennas in MR-MC WMNs. DMesh assumes perfect antenna orientation between communicating node pairs. This may not be the optimum orientation to alleviate interference. DMesh dedicates an exclusive NIC for a wireless link and thus does not utilize network resources efficiently. It also affects the connectivity and results in longer routing paths, hence more interference. In [48], the authors proposed an algorithm to produce joint decisions on routing and channel assignment with practical implementation considerations for MR-MC WMNs with switched beam antennas which require switching and synchronization. They do not take into account the directional interface assignment issue, the antennas are assumed to point to each other during communication. The authors in [51] predefined the antenna orientation using a sectored connectivity graph and formulated their architecture mathematically as a mixed integer linear problem. The problem is then solved to acquire topology, channel assignment, interface allocation and routing decisions. In [52], Liu et al. proposed a topology control method for MR-MC WMNs with directional antennas. The proposed three-step solution starts by constructing a set of routing trees and seeks to balance the traffic among the tree links. In the second step, it performs interface assignment for each node in the tree with the objective of balancing traffic load among the links served by each node. Finally, it performs channel assignment and antenna orientation to minimize interference while covering all the intended neighbors of the node. Based on the method proposed in [52], the authors in [53] presented an improved version of topology control algorithm. In [53], the routing tree construction algorithm is improved in the first step of the solution in [52].

Comparison of topology control mechanisms in MR-MC WMNs

In the previous sections, we have overviewed state-of-the art TC mechanisms which are classified according to their dependence on power control, channel assignment, routing, and directional antennas. Next we further compare the typical classified TC mechanisms in MR-MC WMNs with respect to their inputs, objectives, and techniques used. As shown in Additional file 1: Table S1, twelve TC mechanisms are chosen for comparison and they are identified by the first author and the index of the references, and some TC mechanism also have abbreviations named by the authors in the literature.

It can be seen from Additional file 1: Table S1 that the following parameters can be the inputs of a TC mechanism: node deployment, number of NICs and channels, power profile, antenna type, link and traffic profile, connectivity and topology constraints. Most of the TC mechanisms formulate the TC problem as a optimization problem with respective objectives. The considered objectives include the network throughput (capacity), interference, connectivity, and fairness. Since the formulated optimization problems are normally NP-hard, heuristic approaches are proposed as the viable TC mechanism to achieve the suboptimal solutions.

As we pointed out, TC, PC, CA, and routing are mutually dependent in MR-MC WMNs. Regarding the techniques used, the TC mechanisms can hence employ some or all functions of PC, CA, and routing. PMMUP (Olwal [19]) is proposed as a new power selection MRMC unification protocol that coordinates local power optimizations at the radios of a node to maximize a variable related to the most congested (i.e., the bottleneck) logical link across the network. As shown in Additional file 1: Table S1, a variety of CA schemes are proposed in CLICA (Marina [37]), MesTic (Skalli [38]), Subramanian [39], ComTac (Naveed [40]), Komali and MacKenzie [42]. Both CA and PC functions are employed in TICA (Chaudhry [41]), which use a novel approach of controlling the network topology based on PC before intelligently assigning the channels to the multi-radio mesh router. Moreover, some or all the functions of PC, CA, and routing are employed in the proposed mechanisms of Alicherry [9], TiMesh (Rad [10]),JTCR (Chen [21]), DeSARA (Franklin [43]), and Tang [46]. Such joint approach of TC mechanisms with joint optimization of some or all the functions of PC, CA, and routing often leads to NP-hard complexity. To have a realistic solutions, suboptimal heuristic mechanisms with reduced complexity have been investigated in some mechanisms such as CLICA (Marina [37]), Alicherry [9], DeSARA (Franklin [43]), and Tang [46].

The advantages of joint optimization approaches for TC are that they can take into account multiple objectives of outputs including throughput, interference, connectivity, and fairness. On the other hand, they have disadvantages because they involve more input parameters (like including traffic demands) and hence yield more complex optimization and coordination operations in the network.

Future research directions

As we argued in this article, topology control are coupled together with PC, CA, and routing functions, and it is better to view TC as a management functional block in connection with protocol layers in MR-MC WMNs. This methodology has been demonstrated by many published works with joint optimization of some or all the functions. A unified framework combining all mutually dependent functions is more desirable for MR-MC WMNs. We are expecting to see further exploration of this subject with such a methodology. Joint optimization approach following this methodology can give theoretical understanding of the holistic solution for the TC problem, and we believe that suboptimal heuristic and coordination schemes need to be investigated with reduced complexity for practical realization with such a methodology.

Current research efforts for evaluating the proposed mechanism are mainly based on theoretical performance characterization and simulation modeling, another direction for verifying proposed mechanisms needs further conducting real-world performance evaluation in MR-MC WMN testbed. The real experimental testing may exhibit more issues that are simplified or ignored in theoretical analysis or simulation modeling. The potential issues need to be addressed include the external interference, channel switching time, nonuniform directional antenna patterns, diverse and mixed traffics, and more QoS constraints.

Conclusions

With the growth demand of deployment and advance of wireless technologies, the MR-MC WMN architecture has been started to be adopted as a promising solution. To fully exploit its advantages on improved network performance, new design and operation challenges need to be dealt with. With such a networking architecture, it turns out that many network operations, such as topology control, power control, channel assignment, and routing, are coupled together. We argue that it is better to view TC as a management functional block in connection with protocol layers in MR-MC WMNs. In our survey, this methodology is demonstrated by many published studies with joint optimization of some or all the functions of topology control, power control, channel assignment, and routing. It needs to point out that such a joint optimization approach often leads to NP-hard complexity and hence suboptimal heuristic mechanisms with reduced complexity have been investigated. Considering all envisaged applications, MR-MC WMNs appear to have unprecedented and as yet unrealized potentials. With the recent and future research efforts, a unified framework combining all mutual dependent functions is more desirable for MR-MC WMNs. We are expecting to see further exploration of this subject with such a methodology.

Additional file

Additional file 1: Table S1. Comparison of topology control mechanisms in MR-MC WMNs.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements
This article was supported by the National Natural Science Foundation of China under Grant No. 61062006, the Fundamental Research Funds for the Central Universities under Grant No. G470427, and the Natural Science Foundation of Hainan Province, China under Grant No. 610215.

Author details
[1]School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China. [2]College of Information Science & Technology, Hainan University, Haikou, Hainan 570228, China.

Received: 27 April 2012 Accepted: 3 October 2012
Published: 29 October 2012

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doi:10.1186/1687-1499-2012-324
Cite this article as: Liu and Bai: **An overview of topology control mechanisms in multi-radio multi-channel wireless mesh networks.** *EURASIP Journal on Wireless Communications and Networking* 2012 **2012**:324.