Overview of Wireless Mesh Networks

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Abstract**—**Wireless Mesh Networks (WMNs) introduce a new paradigm of wireless broadband Internet access by providing high data rate service, scalability, and self-healing abilities at reduced cost. Obtaining high throughput for multi-cast applications (e.g. video streaming broadcast) in WMNs is challenging due to the interference and the change of channel quality. To overcome this issue, cross-layer has been proposed to improve the performance of WMNs. Network coding is a powerful coding technique that has been proven to be the very effective in achieving the maximum multi-cast throughput. In addition to achieving the multi-cast throughput, network coding offers other benefits such as load balancing and saves bandwidth consumption. This paper presents a review the fundamental concept types of medium access control (MAC) layer, routing protocols, cross-layer and network coding for wireless mesh networks. Finally, a list of directions for further research is considered.

Index Terms**—**Wireless mesh networks, multi-cast multi- radio multi- channel, medium access control, routing protocols, channel assignment, cross layer, network coding.

I. Introduction

Nowadays, wireless mesh networks (WMNs) are actively investigating with related applications and services. There are several new applications of WMNs such as digital home, broadband Internet access, building automation, health and medical systems, emergency and disaster networking, etc. Also, there are many applications of WMNs by using a multi-cast transmission, for instance, the distribution of financial data, distance education, audio/video conferencing, and IP TV. The major components of a wireless mesh network include wireless mesh routers, wireless mesh clients, such as; (PCs, laptops, PDAs, and cell phones), and access points (AP) or gateways that act like both as Internet routers and wireless mesh routers. The mesh routers in WMNs provide multi-hop connectivity from one host to another, or to the Internet via the access points. Wireless mesh routers can be access points of wireless local area network (WLAN), source nodes of wireless sensor network, or base stations (BS) of cellular network [1]. Fig. 1 shows one example for WMNs infrastructure. Mesh router is generally much more powerful than client in terms of computation and communication capabilities, and have a continuous power supply. They normally stay in static and supply connections and services to mesh clients.

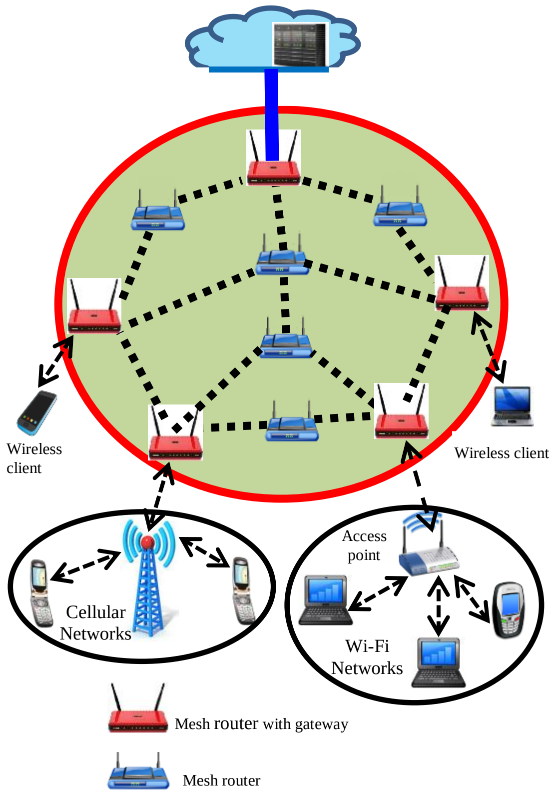

Figure 1. Wireless mesh networks infrastructure

The routers automatically establish and maintain mesh connectivity among themselves, making WMNs dynamically self-organized and self-configured networks. These features bring many benefits to WMNs such as low installation cost, large-scale deployment, reliability, and self-management [2], [3]. Although there are many existing documented works on WMNs, there are some challenges needed to be resolved for all protocol layers. In MAC layer, the challenges are effective channel allocation, efficient spectrum utilization among multiple radios, scheduling of flows for maximum resource utilization, seamless mobility between heterogeneous WMNs, provisioning of multiple QoS metrics, etc. WMNs also need the development of MAC protocols in a multi-radio multi-channel architecture that satisfied QoS metrics requirements such as end-to-end delay, packet loss ratios, link quality, interference, bandwidth and delay jitter.

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The various research challenges of routing protocol for WMNs are mentioned as follows: propose modern routing metrics for new applications, design multi-channel routing protocols that is scalable, efficient, reliability that satisfied QoS metrics. Furthermore, many applications need multi-casting capability. For example, in a community or citywide network, video distribution is a common application [1]-[3]. To date; much research work has been done in multi-casting over wired, but little research has been carried out in multi-casting WMNs for example; load balancing algorithm and multi-path routing, security (authentication and privacy reliability), finally, determine and select the location of the additional mesh gateways that maximizes the network capacity.

The first paper presented a survey of WMNs is for Akyildiz et al. in 2005 [2]. The authors have been presented a detailed investigation of the current state of protocols and algorithms for WMNs. Also they have discussed the open research issues and a research challenges in all protocol layers of WMNs. Then, Akyildiz et al extended their work in [2] and provide a more detailed study on recent advances and open research issues in WMNs [3]. Such as, system architectures, applications, and critical factors influencing protocol design of WMNs. On the other hand, they present theoretical network capacity, protocols and open research issues for WMNs are. In addition, industrial practice, testbeds, and current standard activities related to WMNs are highlighted. Khan et al. [4] gives a basic overview of WMNs and details of IEEE 802.11s while focusing more on the hybrid wireless mesh protocol (HWMP). Mojtaba et al. [5] provide a technical overview of concept; technology and architecture of WMNs. Zou et al. present the state of the art in security for WMNs. Also, various possible threats to security and representative solutions to these threats in WMNs are introduced and analyzed. In addition, the challenges in the security for WMNs are discussed [6].

This paper presents a review of topics that related to wireless mesh networks such as the current state of MAC layer, routing protocols, cross-layer and network coding in multi-cast multi-radio multi-channel. In spite of all open research problems, we believe that WMNs will be one of the most promising technologies for next-generation wireless networks.

The rest of the paper is organized as follows. Section II describes the MAC protocol, and Section III provides the details of routing protocols. Section IV presents the cross-layer and network coding in multi-cast multi-radio multi-channel, and finally, we conclude the paper in Section V.

II. Medium Access Control (MAC) Protocol for Wireless Mesh Networks

The MAC protocol is a process of sharing single communication medium among multiple users with quality of service constraints such as throughput, packet loss ratio, delay, delay jitter, bit rate, and bit error rate. MAC protocols can be classified into two major types, depending on the coordination scheme, centralized MAC and the distributed MAC. For the first one, the communication process is controlled and coordinated by a central node (e.g., AP and BS), and all other nodes can communicate only under the permission of a central node. The distributed MAC is preferred in multi-hop wireless networks because the network itself is distributed in essence. On the other hand, if a centralized MAC is used for multi-hop wireless networks, it lacks enough efficiency owing to the need for maintaining the centralized control among multiple nodes. This is also due to the scalability problem of the MAC protocol. As a result, distributed MAC is extremely necessary for mobile ad-hoc networks (MANETs) and besides for WMNs. However, it is obvious that designing a distributed MAC is a much more challenging task than designing a centralized MAC [7]-[9].

Based on literature review, MAC protocols are classified into four different perspectives. The first one is classified according to the functionality of the protocols, and the problems are resolved such as collision avoidance that included (request to send, clear to send (RTS/CTS) handshake-based MAC, receiver initialized MAC, dual/multiple-channel-based MAC), energy conservation, interference resistance and rate adaptation [1]. The second classification depends on the session initiator. There are sources (sender) initialized, and destination (receiver) initialized MAC. The third classification depends on channel division. They are classified into a single channel and dual or multiple channels MAC. The fourth way of classification is single-radio and multiple-radio. Other researcher's mix between the third and the fourth classifications, as single-channel single-radio MAC protocols, multi-channel single-radio MAC protocols, and multi-channel multi-radio MAC protocols. In this paper, we focus on the last classification as shown in Fig. 2.

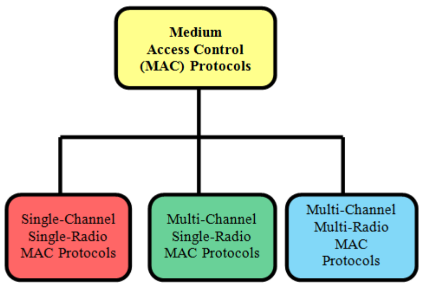

Figure 2. Classification of MAC protocol for WMNs

A. *Single-Channel Single-Radio MAC Protocols*

In this type of classification, many schemes have been proposed such as CSMA/CA improvements, TDMA over CSMA/CA and CDMA MAC, more details explain as follows:

1) *CSMA/CA improvements*

The MAC for WLANs is usually implemented based on carrier sense multiple accesses with collision avoidance (CSMA/CA). In addition, this method can be used in WMNs. In order to improve the performance for WMNs, many schemes have been proposed to fine-tune parameters of CSMA/CA such as contention window size and modify backoff parameters. In literature [10], a dynamically tuned contention window has been proposed to improve the protocol capacity of IEEE 802.11 network. A distributed algorithm that enables each station to tune its backoff algorithm at the run-time is proposed. Simulation results in [10] demonstrated that this scheme could effectively improve throughput performance of CSMA/CA. Different nodes can use different backoff time instead of binary exponential backoff time and can assign different minimum and maximum contention windows [2]. In literature [11], the author has proposed to limit the number of retransmissions of a data frame by a source depending on the application requirements. The authors in [11] have studied how to tune the 802.11 MAC protocol according to multimedia applications' requirements such as end-to-end delay and packet loss rate. The author has used a mathematical model technique to determine the optimal value of this parameter (expected average end-to-end delay or a maximum packet loss rate) for multimedia applications. However, an actual experimentation is needed to evaluate the performance of the proposal in an actual test bed network. Another scheme has been proposed to improve the performance of CSMA/CA in WMNs by improving the virtual carrier sense and a new carrier sensing mechanism called DVCS (Directional Virtual Carrier Sensing) for wireless communication using directional antennas is proposed in [12]. From the simulation results in [12], it has been shown that DVCS can improve network capacity by a factor of 3 to 4 for an Ad-hoc network with 100 nodes when compared to omnidirectional carrier sensing scheme.

2) TDMA over CSMA/CA

Instead of setting different parameters of CSMA/CA to improve the performance CSMA/CA. The authors in the literature [13] proposed new system architecture to integrate TDMA with CSMA/CA. This new MAC protocol consists of the following major functions. Instead of the hardware level retransmission in an 802.11 MAC, a software retransmission is proposed. Based on it, packet reception and transmission can be limited to a particular time slot. As a result, crossing salt - boundaries are avoided. Furthermore, for a coordinate packet transmission in different nodes in the network distributed scheduling, the scheme is developed and the QoS was considered at the time-slot allocation of this scheduling scheme. On the other hand, in [14] a multichannel mode has been proposed to improve the performance of TDMA over CSMA/CA, because the complexity cost of developing a distributed and cooperative MAC with TDMA, and the compatibility of TDMA MAC with existing MAC protocols a few TDMA protocols have been proposed for WMNs.

B. Multi-Channel Single-Radio MAC Protocols

A single-channel MAC protocol (such as IEEE 802.11 DCF) does not work well in a multi-channel environment where nodes may dynamically switch channels [15]. Multiple channels can be used to resolve the capacity limitation by interference, because the interference range is much larger than the communication range in the single channel. This causes to drop the network capacity as the number of hops or as the number of nodes increased. Multiple radios on the same node can be implemented as multiple NICs or one NIC on which multiple radios reside via system-on-chip (SoC) or radio-on-chip (RoC) technique.

There are three different hardware platform's categories to implement multi-channel MAC, multi-channel single-transceiver, and multi-channel multi-transceiver and multi-radio MAC [2],[3]. In addition, there are several single-radio multi-

that have been proposed [14]-[16]. The multi-channel TDMA over CSMA/CA MAC protocol has actually been implemented and applied in mesh networks [14]. In literature [15], a multi-channel MAC (MMAC Protocol) was proposed for Ad-hoc wireless networks that utilize multiple channels dynamically to improve performance. The main goal of MMAC is to solve the multichannel hidden node problem. It solves this problem by synchronizing the RTS/CTS based channel negotiation process among all nodes. In this case, channel for different pairs of communicating nodes will not interfere with each other. The proposed protocol enables hosts to utilize multiple channels by switching channels dynamically, thus increasing network throughput, especially when the network is highly congested. The proposed protocol requires only one transceiver for each host, while other multi-channel, the MAC protocols require multiple transceivers for each host. The simulation results in [15] showed that the MMAC achieved higher throughput and lower average packet delay than IEEE 802.11 MAC. However, the overall design of MMAC is far from a practical MAC protocol that can be applied to WMNs.

In addition, there are several problems that have not been solved in this protocol. For example in [15], the RTS/CTS is an optional function of DCF, whereas, it is assumed that RTS/CTS always work in IEEE 802.11 DCF. A large channel switching time which most time may be more than 224s causes noticeable delay, and as such, leads to significant performance degradation of a multi-channel MAC protocol. Moreover, a large number of hops and nodes in the network also present a serious difficulty in achieving synchronization between the nodes.

C. Multi-Radio MAC Protocols

There are two advantages of multi-radio MAC protocols over a single-radio MAC protocol. These advantages are obvious as the same node can have simultaneous communications on different radios. The first advantage is that the multi-radio MAC can achieve higher network capacity and throughput than a single-radio MAC, while on the second count, the multi-radio MAC protocol does not need to switch channels on a wireless radio [3]. Several researchers have proposed multi-radio communications for WMNs, but most of them do not consider how the MAC protocol was designed. On the other hand, other researcher's have focused on how the channels are assigned on different radios. One of the protocols that was proposed is a multi-radio unification protocol (MUP) for IEEE 802.11 Wireless Networks [17]. The main goal is to optimize local spectrum usage via intelligent channel selection in a multi-hop wireless network. This protocol enables scalable multi-hop wireless networks. Nodes in a MUP enabled multi-radio multi-hop network to achieve a 70% increase in throughput and 50% improvement in delay.

However, there are several issues remain unresolved such as; the channel switching mechanism is not justified; RTT measurement does not reflect traffic load; the hidden node issue is not solved. The MAC addresses of a neighbor may not be always detected, channel allocation on each NIC is not optimal, and packet rearrange is needed when channels are switched [3]. A channel assignment algorithm, TICA (Topology-controlled Interference aware Channel-assignment Algorithm) to improve the network throughput by minimizing interference is proposed in [18].

In literature [19], a new MAC algorithm which can increase the RTS success rate called List-Based Medium Access Control (LBMAC) is proposed to resolve the Head-of-Line (HOL) blocking problem. HOL blocking problem is considered as one of the major reasons for degradation of the performance in wireless mesh networks (WMNs). By using this algorithm based on the CSMA/CA algorithm, the backoff time reduced. The results show that a higher throughput and a lower time delay are feasible and realizable using a LBMAC algorithm than IEEE 802.11 MAC protocol. This is done by scheduling packets based on an address list and reducing the increase rate of backoff time. A joint channel/radio assignment and time scheduling algorithm for multiple radio (multiple channel access capable WMNs) was proposed in [20]. This scheme eliminates the interference between wireless routers and achieves a traffic-wise resource allocation, and as a result improves the overall achievable network throughput while accounting for data traffic requirements. The proposed scheme is referred to as traffic aware interference-free scheduling (TAIFS). It used to increase channel utilization and improves the network capacity. The TAIFS exploits the channel switching capability of the radio interfaces. Furthermore, it has a given set of active paths and active link loads. In addition to get the maximum capacity of the links with respect to their traffic loads, the TAIFS distributes the time and channel resources among the active links. The authors in [20] focus on link scheduling and channel assignment algorithms rather than on routing techniques.

A channel assignment problem for multi-channel multi-interface (radio) WMNs has been studied in [21], and the main goal is to find a fixed channel assignment which maximizes the number of bidirectional links that can be activated simultaneously, subject to interference constraints [21]. Furthermore, it is to find the maximum network connectivity as well as the minimum network interference. The author presented an optimization model for channel assignment algorithm using multi-objective genetic algorithms (MOGAs) with simulations on NS2. In [22], the author imported the NSGA-II for channel allocation on, and good results were achieved in improving the network throughput. In literature [23], the proposed multi-channel MAC protocol was designed and modified based on literature [24] to reduce the interference range and also, eliminate the hidden terminal problems for multi hop wireless mesh networks.

There are two types of channels in multi-radio multi-channel wireless networks. The first one is the control channel for passing system control and channel setup messages. The second type is the data channel which is for data frame transmission after a connection has been established successfully. The control channels should always be on, but those for the data channels can be switched on when needed. The main design goal in [23] is to offer a platform for resolving channel assignments in different wireless hops in a communication network. It resolves the interference range issue, and hence link-layered terminal problems. The results show that the proposed MAC design had a better throughput performance. Review of existing works demonstrated extensively that using multiple radios with multiple channels will sufficiently lead to enhanced capacity and improved throughput, yet with a decrease in interference of WMNs. However, there is a attendant problem of cost and power consumption at the mesh point of view. Consequently, the number of the mesh routers had to be increased in order to adequately compensate for the shortcomings. One possible solution to maintain a balance between interference, performance, and cost is to use a multiple channel with fewer radios such that switching among multiple channels is a possibility rather than the use of channel per radio. In literature [25], a channel-switching method, called the traffic-aware switching scheme (TRASS) which is proposed for a mesh point with a limited number of radios. To avoid packet loss during channel switching, the TRASS uses the existing IEEE 802.11 mechanisms such as hybrid-coordination function-controlled channel access and power saving method [25]. TRASS selects the next channel according to the radio utilization of each channel during its previous staying periods. The results demonstrated a (2, 1), i.e., two-channel single-radio, over (1, 1) throughput improvement of 75%.

III. Routing Protocols for Wireless Mesh Networks

Several advantages of WMNs include flexible network architecture, easy deployment and configuration, self-healing, and self-organization. For these reasons, it is a more flexible solution to provide wireless network access and for that it is becoming popular. At the same time, routing in WMNs is considered as an interesting research area. There are several challenging tasks in the WMNs routing, and it's receiving considerable attention from researchers in recent times [26]. More importantly, WMNs nodes are fixed and do not need batteries to operate. Therefore, WMNs routing protocols must focus on reliability and performance improvement rather than mobility or energy consumption. Accordingly, this has led to the development and improvement of different routing protocols for WMNs. On the contrary, it is quite difficult to determine, which routing protocol performs best under a number of different network scenarios and applications, such as traffic, load balance, capacity, delay, and increasing node density.

In this paper, we try to provide an overview of routing protocols that have been proposed in previous literatures. In a large network, route updates consume part of the available bandwidth and increase channel congestion. Consequently, the traditional distance vector and link state routing protocols do not scale in large mobile ad hoc networks (MANETs) [27], [28]. To overcome these problems which are associated with the link state and distance vector protocols, a number of routing protocols have been proposed for MANETs.

Ad-hoc routing protocols for WMNs are classified into three kinds: (1) proactive (table-driven), (2) reactive (on demand), and (3) hybrid [27]-[29]. Fig. 3 shows a summary classification of routing protocol for WMNs. In general, proactive routing protocols such as OLSR (Optimized Link State Routing) [30] and DSDV (Destination-Sequenced Distance Vector) [31] are more suitable for a stationary network. In these types of protocol, the routes to all destinations are determined at the startup, and maintained by using a periodic path update process. However, reactive routing protocols such as AODV (Ad hoc On-demand Distance Vector) [32], DYMO (Dynamic MANET On-demand Routing) [33], and DSR (Dynamic Source Routing) [34] are better for mobile networks with a high mobility [35]. The routes are determined only when they are required by the source using a route discovery process. In contrast, hybrid routing protocols, such as ZRP (Zone Routing Protocol) [36] and ZHLS (Zone-Based Hierarchical Link-State) [37] combine the basic properties of the first two classes of protocols into one. For several applications, a client in WMNs is mobile, but it can vary between being mobile and being stationary. Therefore, use the hybrid routing approach with the ability to adapt client mobility can improve the performance and scalability of WMNs by partitioning a network into several different zones.

A. Proactive Routing Protocols (Table-Driven)

This type of protocol operates like a traditional routing protocols on wired networks. This means the routes maintain at least one route to any destination in the network. Typical of these routing protocols, every node in a network ensures a routing table to store route information so that the routes are always available when needed. The main advantage of this category of the protocol is to enable the node quick access to route information and also, to establish a session promptly. However, they have serious disadvantages of increasing routing overhead and waste bandwidth. This is because each node periodically sends the routing information throughout the entire network, and as such, keeps the routing information in different tables. These tables are periodically updated if the network topology changes.

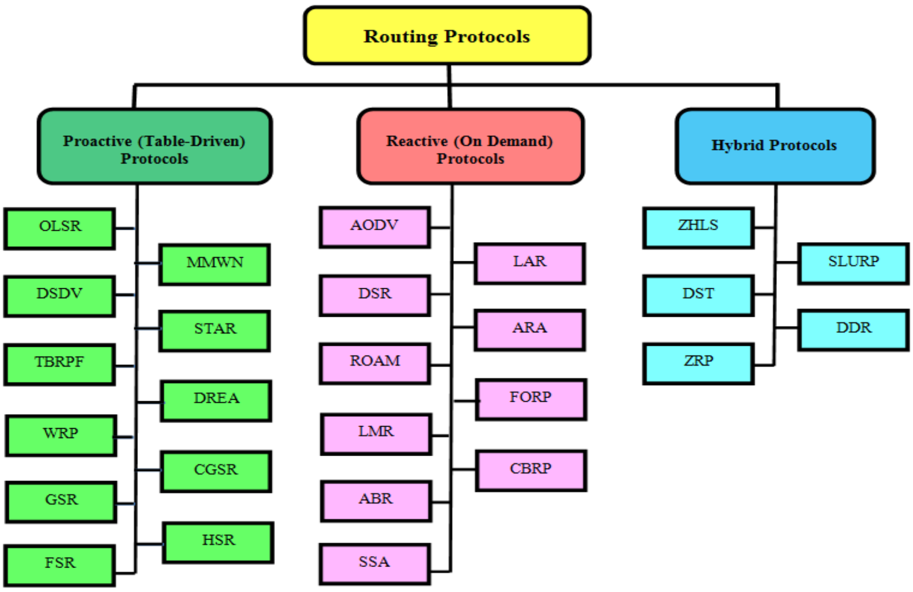

Figure 3. Classification of routing protocol for WMNs

There are several different proactive protocols for example, Topology Broadcast reverses Path Forwarding (TBRPF) [38], Destination-Sequenced Distance Vector (DSDV) [39], Wireless Routing Protocol (WRP) [40], Global State Routing (GSR) [41], Fisheye State Routing (FSR) [42], Source-Tree Adaptive Routing (STAR) [43], Multimedia Support Mobile Wireless Networks (MMWN) [44], Distance Routing Effect Algorithm For Mobility (DREAM) [45], Cluster-head Gateway Switch Routing (CGSR) [46], Hierarchical State Routing (HSR) [47] and Optimized Link State Routing (OLSR) [30]. In this paper, the authors are positively disposed to OLSR.

B. Optimized Link State Routing (OLSR)

OLSR is a type of proactive protocols [30], [48], which is a point-to-point routing protocol, operatively based on the traditional link state routing protocol. In this protocol, each node in the network maintains topology and the routing information of the network by periodically exchanging the link state messages. One good thing about this protocol is that it reduces the size of control message and so is the number of rebroadcasting nodes during each route update. It does that by using multipoint replaying (MPR) strategy [30]. Each node in the network selects a set of neighboring nodes to retransmit its packets during each topology update. This set of nodes is called the multipoint relays. By using periodically broadcasts hello messages, each node periodically broadcasts a list of its one hop neighbors to select the MPRs. From the list of nodes in the hello messages, each node through exchanging the HELLO message selects a subset of one hop neighbors, which covers all of its two hop neighbors. Moreover, any node which is not in the set can read and process each packet but do not retransmit. In essence, this effectively reduces the number of rebroadcasting nodes through the use of multipoint relaying, by randomly selecting only a few numbers of neighboring nodes to rebroadcast the message. In effect, the network scalability is increased. In contrast, the original OLSR is not quite suitable for WMNs since it considers the minimum hop count metric to determine the best path to reach a destination. It does not take into account the link quality (throughput, delay, capacity, interference, etc.) while computing routing tables. In multi-hop networks, the hop count metric has been shown not to be efficient [49], 50].

C. Reactive Routing Protocols (On-demand)

In literature [51], a traditional link-state protocol (OLSR) is developed to improve the throughput and packet delivery ratio, while minimizing routing overhead and delay.

The modified protocol takes advantages of static router backbone of wireless mesh networks to calculate a more stable and optimal route with the minimum hop count, in order to improve the network performance. Furthermore, the protocol uses the concept of multipoint relays (MPRs) as used in OLSR. There are three specific functionalities of the M-OLSR protocol over the OLSR protocol. The first is to improve HELLO exchange, second is topology dissemination, and finally, the routing table calculation. Three key performance metrics (throughput, packet delivery ratio, and normalized routing overhead) were evaluated to study the effectiveness of MOLSR. Simulation results [51] using NS-2 simulations in different scenarios demonstrate better scalability of traffic load and mobility in a sparse and dense network.

These types of protocols request a route to a destination only when a node (source) has a data packet to send. Otherwise, the node will have no request. Normally, this type of protocols used a flooding mechanism to discover a route. By maintaining information for active routes only this reduces the overheads in proactive protocols [26]. Reactive protocols can be classified into two categories namely: source routing and hop-by-hop routing. In source routing on-demand protocols [52], [53], each data packets carry all the complete address from the source to destination. Accordingly, each intermediate node in the network forwards these data packets according to the information that is kept in the header of each packet. Therefore, the intermediate nodes do not need to maintain routing information for each active route in order to forward the packet to the destination. However, in large networks, the source routing protocols do not perform well. The reason is when the number of intermediate nodes in each route increase, the probability of route failure and the amount of overheads in each header of each data packet will increase too.

On the other hand, in hop-by-hop routing or point-to-point routing [26], [32] each data packet only carries the destination address and the next hop address. Therefore, to forward each data packet towards the destination, each intermediate node in the path to the destination uses its routing table to forward a data packet. The disadvantage of this protocol is that each intermediate node must store and maintain routing information for each active route, and also; each node is required to be aware of their surrounding neighbors through the use of beaconing messages. The advantage of this strategy is that routes are adaptable to the dynamically changing environment of MANETs.

There are several different reactive routing protocols that have been proposed to increase the performance of reactive routing protocols. Such reactive routing protocols include: Ad -hoc on-demand distance vector (AODV) [32], Dynamic source routing (DSR) [34], Routing on-demand acyclic multi-path (ROAM) [53], Light-weight mobile routing (LMR) [54], Associativity-based routing (ABR) [55], Signal stability adaptive (SSA) [56], Location-aided routing (LAR) [57], Ant-colony-based routing algorithm (ARA) [58], Flow oriented routing protocol (FORP) [59], Cluster-based routing protocol (CBRP) [60]. In this paper, we highlight the ADOV and DSR.

1) Ad hoc on-demand distance vector (AODV)

The AODV [32] routing protocol is based on DSDV and DSR [34] protocols. This protocol uses the route discovery procedure as similar as in DSR, while it uses the periodic beaconing and the sequence numbering procedure of DSDV. However, there are two major differences between DSR and AODV. The most distinguishing difference is that in DSR each packet carries full routing information, whereas in AODV, the packets carry the destination address. This means that AODV has potentially less routing overheads than DSR.

The other difference is that, the route in DSR replies to the address of every node along the route, whereas in AODV, the route replies only the destination IP address and the sequence number. The advantage of AODV is that it is adaptable with highly dynamic networks. However, a node may experience large delays during route construction, and as such; link failure may initiate another route discovery, which ultimately introduces extra delays and consumes more bandwidth as the size of the network increases [61].

2) Dynamic source routing (DSR)

In this protocol, each packet is required to carry the full address from the source to the destination. Therefore, this protocol will not be very effective in large networks, because the amount of overheads in the packet will increase as the network diameter increases. Hence in highly dynamic and large networks, the overhead may consume most of the bandwidth [26]. However, this protocol has a number of advantages over routing protocols, such as AODV [32], LMR [62], and TORA [63]. These advantages are: better protocol performance in a small and moderate size network, where the nodes in this protocol can enter sleep mode to conserve their power (as it does not require any periodic beaconing or hello message exchanges, which in turn saves a considerable amount of bandwidth in the network). Another advantage is that the nodes can store multiple routes in their route cache, which means that the source node can check its route cache for a valid route before initiating route discovery. If a valid route is found, then there is no need for route discovery. This is very beneficial in a network with low mobility since the routes stored in the route cache will be valid longer [26].

There are two types of mechanisms in DSR, which are, routing discovery, and routing maintenance. Routing discovery is used to calculate the route from source node to a destination node, while routing maintenance is used to monitor the available current route. The routing maintenance is divided into a point to point confirmation and end to end confirmation. If the intermediate nodes are damaged or mobile, then the data packets cannot get to the destination node successfully. So, the current route becomes useless and then DSR will use routing maintenance to monitor the availability of the present route. If the monitor found out that the current route is a failure, then the DSR protocol locates a new route using routing discovery [61].

D. Hybrid Routing Protocols

These types of protocols are new generations of protocols, which are both proactive and reactive in nature. It combines the advantages of proactive and reactive protocols by adopting the routing scheme to the characteristics of the network, such as: topology, size, mobility, and traffic pattern. In fact, they are designed to increase scalability and reduce the route discovery overheads. The most hybrid protocols proposed, until now, are zone-based, which means the network is partitioned or seen as a number of zones by each node [26], [35]. In this case, the routing protocol can employ a proactive strategy for intra-cluster communication and a reactive routing strategy for inter-cluster communication. There are several numbers of different hybrid routing protocol proposed for MANETs, for example; zone-based hierarchical link state (ZHLS) [64], scalable location updates routing protocol (SLURP) [65], distributed spanning trees based routing protocol (DST) [66], distributed dynamic routing (DDR) [67] and zone routing protocol (ZRP) [68]. In this paper, we will highlight the ZRP.

1) Zone routing protocol (ZRP)

In this protocol, the nodes have a routing zone, which defines a range that each node is required to maintain network connectivity proactively [68]. For this reason, routes are immediately available for nodes within the routing zone. In contrast, for nodes that are outside the routing zone, routes are determined on-demand (i.e. reactively), and it can use any on-demand routing protocol to determine a route to the required destination [61]. One advantage of this protocol is that it has reduced the amount of communications overhead if compared to be proactive protocols.

On the other hand, it reduced the delays, which are associated with reactive protocols such as DSR. The disadvantage of this protocol is that it can behave like a proactive protocol for large values of routing zone, while for small values; it behaves like a reactive protocol. Hybrid routing protocols have the potential to provide higher scalability than pure reactive or proactive protocols.

Although, there are many routing protocols which are available for ad-hoc networks, the need for the design and improvement of the routing protocols for WMNs must consider multiple performance metrics, robustness, and scalability. Similarly, classified routing protocols into reactive and proactive routing protocols are coming from the ad-hoc network (as previously stated) where the mobility and power consumption is important. Also, the routing protocols should consider the benefit of mesh network such as no mobility, and each node has more than one radio due to the differences between mesh network and mobile ad-hoc network. Therefore, the routing protocols can be classified into single-radio and multi-radio routing protocols, depending on radio technology that used [27].

E. Single Radio Routing Protocol

In this type of routing protocols, each node that works in the network has only single radio. One example of this type is AODV-ST [69]. It is a hybrid routing protocol, and so, it uses a reactive strategy to find routes between mesh routers, and proactive strategy. This is done in order to discover routes between the mesh routers and the gateways. To initiate the creation of spanning trees, the gateways periodically broadcast special RREQ packets, and in this case, all nodes receiving these RREQ packets create a reverse route to the gateway. Also, these nodes send a RREP packet to the gateway in order to enable the formation of forward routes. To ensure successful transmission, a packet on a link AODV-ST uses the Expected Transmission Time (ETT) routing metric that measures the expected time. In addition, this protocol was developed specifically for infrastructure mesh network, which has more than one gateway with the aim of providing Internet access to Mesh Clients. In [70], the multi-channel routing protocol (MCRP) for single radio ad hoc topology was proposed. To switch the interface to non-interfering channel, it uses the channel switching mechanism for this purpose. The advantage of this protocol is the ability to utilize the wireless spectrum by utilizing the multi-channel. By allocating different channel to different flows, network performance can be improved and the interference between simultaneous transmissions can be minimized.

F. Multi-Radio Routing Protocols

In this type of protocol, each node is equipped with at least two radios. This type of routing protocols provides a great improvement in network performance and increase the capacity and scalability over traditional mobile ad-hoc networks, instead of modifying the MAC protocol. One example of this protocol is a multi-radio LQSR (MR-LQSR) [70], which proposed the WCETT (Weight Cumulative Expected Transmission Time) metric. This metric takes into account both the loss rate and the bandwidth of a link with the minimum hop count. Furthermore, it is a tradeoff between channel diversity and path length. The goal of MR-LQSR is to choose a high-throughput path between a source and a destination. The results demonstrated that the shortest path algorithm does not perform well when network nodes have multiple radios.

In [71], AODV-MR was proposed to improve AODV to work in multi-radio wireless mesh network. AODV-MR broadcast the RREQ message on all interfaces and assumes that each node has at least one common channel with a neighbor. By using this protocol, the network capacity increases because it causes a lower degree of interference and contention due to distributed traffic across multiple non-overlapping channels. In contrast, it uses a hop count as a metric, so AODV-MR does not distinguish between the client node and backbone nodes. In this case, the path selection may select fewer capacity paths. From other side, hybrids mesh Ad-hoc on-demand distance vector routing protocol (AODV-HM) was proposed [72]. This protocol modified the AODV-MR by using the maximize channel diversity to select the best link, and replace the AODV-MR hop-count metric with the minimum hop count mesh router. It means that the selected path with the minimum number of mesh router on the path. In addition, the AODV-HM is considered a node-aware routing protocol, which means; it can successfully differentiate between the multi-radio mesh routers and single-radio mesh clients.

In [72], an advanced routing protocol was proposed to improve DSR and avoid the broadcast storm problem. It handles the congestion question by transmitting the packets based on the distance threshold and congestion threshold. Furthermore, the best broadcast packet forwarding node can be determined, and also, resolve the bad impact problem due to broadcast storms by joint distance threshold and the congestion threshold together. The simulation results demonstrated that the improved routing protocol has a bigger throughput than before. In addition, the simulation results show that each node forwards data efficiently by using this new modified protocol.

In [61], a comparison and performance evaluation for on demand routing protocols, DSR and AODV were presented. They used the same routing discovery mechanism (Request-Response) based on the flooding method. On the one hand simulation results using the OPNET simulation models show that, routing discovery time of DSR is less than AODV, this is because, each node in the routing of AODV will establish and maintain the routing table, while the network delay of DSR is longer than AODV. The reason is that the head of each data packet in DSR carries the routing information that increases the length of the packet and the time delay in queuing and processing.

On the other hand, the network throughput of AODV is higher than DSR. This is because the routing mechanisms of these protocols are different, in which DSR is based on dynamic source routing, and AODV is based on purpose-driven. Additionally, the simulation results show that the DSR is not suitable for wireless transmission, while AODV is suitable for wireless transmission with rapid change of network topology. In [73], the performance evaluation and comparison of the routing protocols that are used in wireless Ad-hoc networks such as DSDV, OLSR, AODV, and DSR was proposed. Three different kinds of tests for considering the network size, network load and the mobility of nodes were performed. Although, it is difficult to find the ideal and the best routing recommendation for WMNs, but one can consider the OLSR as the best in data delivery ratio and end-to-end delay. We can see the AODV performs better in high mobility and network load. However, scalability is still one of the main problems. A proposed solution is using multiple radios multiple channels in order to improve performance and provide better capacity of the network.

IV. Cross-Layer and Network Coding in Multi-Cast Multi-Radio Multi-Channel WMNs

One of the most effective approaches to enhance the throughput for WMNs is to use systems with multiple channels and multiple radios per node. Simultaneous transmission by neighboring nodes on the same channel of a wireless network will lead to packet collision and direct effect on the network performance in terms of data delivery ratio and delay. In WMNs, it is essential to balance the traffic across different parts of a network. This is done to minimize the number of transmissions made in a neighborhood, which reduces the occurrence of traffic congestion and wireless contention. This needs to be done through a joint design of routing, which distributes the traffic to different paths of a network, and channel assignment. Moreover it distributes traffic across all available channels [74].

Due to the performance of multi-radio multi-channel, WMNs depend significantly on how the channels are assigned to the radios and how traffic is routed between the access points and the gateways. Multi-channel multi-radio (MCMR) networks require efficient channel assignment (CA) algorithms to determine which channel a link should be used for data transmission in order to maximize network throughput. The problem of CA has been studied extensively for unicast communications [75], [76]. In a multi-channel environment, any two nodes can only communicate with one another if they are in the transmission range of one another and they have at least one radio set on a common frequency. For this reason, the processes of routing and channel assignments are very much interrelated.

There are several proposed approaches addressing the challenges in joint channel assignment and routing in different ways [77]-[83]. For instance, cross-layer proposals comprise jointly optimum routing and scheduling, jointly congestion control and scheduling, jointly optimal routing, scheduling and power control. Although there are many ongoing researches on WMNs, joint channel assignment, and routing are essential yet challenging issues for multi-radio multi-channel WMNs still sustain. Though several works are presented in the existing literature to approach this problem, the key question – how to ensure that the resulting network performance can closely track the optimal solution under high-traffic variability without incurring too many overheads remains unanswered [74].

In [76], Minh *et al*., proposes an approach namely CLNC (Cross-Layer Network Coding), which joints power control and routing with random linear network coding to improve throughput for the single source multi-cast problem in multi-cast wireless mesh networks. They solve multi-cast problem using two algorithms. An optimal power algorithm is used to choose the best power level of node, and network coding technique is used to transmit packets on the network. They consider the first three layers of protocol stacks (physical layer, MAC layer, and network layer) for cross-layer design. The simulation results show that when the number of receivers is high, CLNC's throughput is higher, and at least 30 percent higher than that of known methods such as AODV, DSDV and DSR are higher than that of MAODV.

Yuan *et al.* [84] proposed a cross-layer optimization approach of jointing flow routing and power control in a multi-cast. The main technique used in this paper is the method of dual decomposition for convex optimization problems. Luigi et al. [85] proposed a cross-layer heuristic approach that joints power control and routing in wireless mesh networks. They do not perform power optimization and route discovery at once, but they structure the algorithm in two sub-algorithms that involved local power optimization algorithm and the route discovery algorithm for unicast transmission. In [86], Kai Li and X. Wang developed a cross-layer optimization framework for designing multi-radio/multi-channel wireless mesh networks employing network coding to support multiple unicast applications. The broadcasting feature of the wireless environment plays an important role in realizing the achievable gain of network coding. The authors [86] focused on solutions that can efficiently utilize the limited resource to support multiple unicast applications by routing and network coding. They also proposed a network code construction scheme based on linear programming. To solve the optimization problem, a column-generation-assisted primal dual method was proposed. In [87], Lei You1 et al, present a cross-layer algorithm for joint optimization of congestion control, routing, and scheduling in wireless multi-hop networks with network coding. The authors introduced a virtual flow variables in the formulation of the capacity region of the networks. Furthermore, they used dual decomposition and sub gradient methods for solving the utility maximization problem. The simulation results show that network coding in the proposed joint optimization algorithm can interact adaptively and optimally with other components in different layers, and thus yield higher performance than the routing scheme without network coding. Alicherry and Bhatia [88] proposed a mathematical formula for the joint channel assignment and routing problem taking into account the interference constraints, the number of channels in the network and the number of radios available at each mesh router. Thereafter, they used this formulation to develop a solution for the problem that optimizes the overall network throughput.

A multi-cast is a form of communication that delivers information from a source to a set of destinations simultaneously in an efficient manner. Important applications of multi-cast include: distribution of financial data, billing records, software, and newspapers; audio/video conferencing; distance education; IP television; and distributed interactive games. Although a multi-cast is required to support many important applications, research on multi-casting in multi-radio multi-channel WMNs is still in its infancy [75]. The problem of channel assignment (CA) has been studied extensively in the context of unicast communications [89]-[93], and most assumes orthogonal channels. CA for multi-cast, however, has only been addressed recently [75], [94], [95]. Zeng et al. [94] proposed a CA algorithm for multi-cast in multi-radio multi-channel WMNs called multi-channel multi-cast (MCM). This algorithm suffers from low performance caused by the hidden channel problem (HCP), and from the inconvenient use of interference factors. Nguyen also proposed a CA algorithm named minimum interference multi-channel multi-radio multi-cast (M4) that eliminates the HCP [75]. The algorithm enables the nodes in a multi-cast tree to operate with minimum interference. They considered both orthogonal and overlapping channels such as those in IEEE 802.11b/g systems, and discussed the drawbacks of the MCM algorithm [94]. Then they proposed the solution to the HCP as well as an optimization function that does not rely on the computation of interference factors. Advantages of the proposed CA algorithm include its simple implementation and high performance; the experimental results show that M4 outperforms MCM in various scenarios with respect to the average packet delivery ratio (PDR), throughput and end-to-end delay.

All the previously mentioned researches did not use the network coding with joint channel assignment and routing problem, especially for multi-cast multi-radio multi-channel WMNs. One of the most effective approaches to enhance the aggregate network throughput is to use systems with multiple channels and multiple radios per node [74]-[77].

A multi-radio multi-channel node can transmit on one channel and receive on another at the same time using two different radios without interfering with each other. As a result, multi-radio multi-channel wireless network at least doubles the throughput, since each node is now in full-duplex mode, being able to transmit and receive simultaneously [75]. However, to ensure such interference free communication, all the nodes within each other's interference range must be on different channels. This problem of making sure that all the interfering nodes are assigned different channels is known as the channel assignment problem. The channel assignment problem becomes more challenging to solve when each node is equipped with multiple radios. This is because when a node is equipped with multiple radios (if both the radios operate on the same channel), then there is interference from a node own radio which leads to packet collisions. However, if it can be ensured that in a node, if each of the multiple radio interfaces operates on different channels, then this will improve the network performance. So, multi-radio multi-channel networks require efficient algorithms for channel assignment (CA). This is a task of determining which channel a link should use for data transmission in order to minimize interference for maximum throughput. The benefits of using multi-radio multi-channel are studied in [88], which consider channel assignment. The CA problem can be classified into three approaches: (1) CA first, routing second [96], [97]; (2) routing first, CA second [98], [99]; and (3) joint CA and routing [77]-[83], [88], [100], [101]. Recently, the development in the network coding field [102]–[108] have demonstrated the potential of network coding and its application for throughput maximizing of WMNs. Network coding has been applied successfully in WMNs.

Network coding (NC) thus promises to be a vital tool which can be used to reduce intra-network interference (by reducing the number of transmissions required) thereby freeing up bandwidth for additional traffic. This can be seen as an increase in the traffic carrying capacity of the WMNs compared to traditional approaches. Wireless network coding (WNC) can be categorized into the following two types: i) the conventional WNC as in [107] and ii) the analog NC as in [109], [110]). In the conventional WNC scheme, we need only three-time slots to complete the two-way relay transmissions. On the other hand, using analog NC, the two-way relay transmissions can be completed in just one-time slot. The analog NC cannot only exploit the broadcast nature of the wireless channel, but also takes advantage of the native physical-layer coding ability by analogously mixing simultaneously arrived radio waves at the relay nodes [104].

V. Directions for Further Research

In this section, we provide a few directions for further research in WMNs.

1) A cross layer approach design that joints the first three layers of protocol stacks (physical layer, MAC layer and network layer) for designing multi-radio multi-channel wireless mesh networks (MRMC-WMNs) with employing network coding to support multi-cast applications.
2) Joints channel assignment and routing with analog network coding to improve throughput in multi-cast MRMC-WMNs. The analog network coding can not only exploit the broadcast nature of the wireless channel, but also take advantage of the native physical-layer coding ability by analogously mixing simultaneously arrived radio waves at the relay nodes.

3) Propose a mathematical modeling technique for optimizing the maximum network throughput and minimization end-to-end delay in MRMC-WMNs/
4) In order to minimize the interference factor that defined is the ratio of the interference range to the transmission range. An optimal power algorithm is used to adjust the power of the transceiver node. In order to minimize interference, the power adjustment of the transceiver is used to change the transmission range.
5) Propose a channel assignment algorithm (CAA) for MRMC-WMNs to minimize the interference between mesh routers, and ensure network connectivity. Also, in order to prevent throughput degradation, the inter-radio interference (inter-antenna interference), must be considered in channel assignment for each radio. There is a relationship between the channel separation and antenna distance in terms of the inter-radio interference.
6) Propose or develop a new approach of network coding to increase the transmission capacity and improves throughput of a WMNs.
7) Propose a joint network and channel coding scheme for reliable multi-hop multi-radio multi-channel wireless mesh networks (MHMRMC-WMN).

VI. Conclusions

This paper presents a detailed study on recent advances and open research issues in WMNs. Many fundamental issues in WMNs such as MAC protocols, routing protocols, cross-layer and network coding in a multi-cast multi-radio multi-channel were presented in this paper. By combining between cross layer optimization and network coding, many benefits can be derived including maximum multi-cast throughput. Network coding has been successfully applied to contemporary WMNs to reduce intra-network interference and enhance the capacity of the WMN. Intra-network interference, i.e. interference in the network caused by the network, is one the most important capacity/throughput limiting factors in WMNs.

References

[1] I. F. Akyildiz and X. D. Wang, *Wireless Mesh Networks*, A John Wiley and Sons, Ltd, Publication, 2009.

[2] I. F. Akyildiz and X. D. Wang, “A survey on wireless mesh networks,” *IEEE Communications Magazine*, vol. 43, no. 9, pp. S23 - S30, 2005.

[3] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer Networks*, vol. 47, pp. 445-487, March 15, 2005.

[4] M. K. Ali, S. M. Reza, and H. Moradi. "A brief overview of wireless mesh networks with focus on routing," *IEEE-ICC*, 2007.

[5] M. Seyedzadegan, M. Othman, B. M. Ali, and S. Subramaniam, "Wireless mesh networks: WMN overview, WMN architecture," in *Proc. International Conference on Communication Engineering and Networks IPCSIT*, 2011.

[6] Y. Liu, Q. Q. Ruan, and Y. He, "A survey on security of wireless mesh networks," *Information Security and Communications Privacy*, vol. 1, pp. 051, 2010.

[7] U. T. Nguyen, “On multi-cast routing in wireless mesh networks,” *Journal Computer Communications*, vol. 31, pp. 1385–1399, 2008.

[8] S. Seth, A. Gankotiy, and A. Jindal, “Current state of art research issues and challenges in wireless mesh networks,” in *Proc. Second International Conference on Computer Engineering and Applications*, 2010.

[9] G. R. Hiertz, S. Max, Y. P. Zang, T. Junge, and D. Denteneer, “IEEE 802.11s MAC fundamentals,” in *Proc. IEEE International Conference on Mobile Adhoc and Sensor Systems*, October 2007, pp. 1-8.

[10] F. Cali, M. Conti, and E. Gregori, “Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit,” *IEEE/ACM Trans. Networking*, vol. 8, no. 6, pp. 785–799, 2000.

[11] F. Filali, “Dynamic and efficient tuning of IEEE 802.11 for multimedia applications,” in *Proc. 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 2, 2004, pp. 910 – 914.

[12] M. M. Takai, J. Martin, A. AifengRen, and R. Bagrodia, “Directional virtual carrier sensing for directional antennas in mobile ad hoc networks,” in *Proc. Sixth ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC)* , 2002, pp. 183–193.

[13] X. Wang, W. Wang, and M. Nova, “Distributed TDMA for wireless mesh networks,” US Patent Serial Number: 11/076738.

[14] X. Wang, V. Rollinger, A. Patil, G. Chao, W. Wang, and M. Nova, “Distributed multichannel wireless communications,” US Patent Serial Number: 11/420668, 2006.

[15] J. So and N. Vaidya, “Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver,” in *Proc. ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC)* , 2004, pp. 222–233.

[16] P. Bahl, R. Chandra, and J. Dunagan, “SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks,” in *Proc. ACM Annual International Conference on Mobile Computing and Networking (MOBICOM)*, 2004, pp. 216–230.

[17] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, “A multi-radio unification protocol for IEEE 802.11 wireless networks,” in *Proc. Annual International Conferences on Broadband Networks (BroadNets)*, 2004.

[18] A. U. Chaudhry, R. H. M. Hafez, O. Aboul-Magd, and S. A. Ahmoud, “Throughput improvement in multi-radio multi- channel 802.11a-based wireless mesh networks,” *IEEE Communications Society Subject Matter Experts for Publication in the IEEE Globecom Proceedings*, 2010.

[19] M. Y. Jeong, B. G. Choi, J. Y. Lee, and M. Y. Chung , “A list-based medium access control algorithm in IEEE 802.11 wireless mesh networks,” in *Proc. ICACT*, 2010.

[20] N. Chakchouk and B. Hamdaoui, “Traffic and interference aware scheduling for multiradio multichannel wireless mesh networks,” *IEEE Transactions on Vehicular Technology*, vol. 60, no. 2, February 2011.

[21] J. Chen, J. Jia, Y. Y. Wen, D. Z. Zhao, and J. R. Liu, “ Optimization of resource allocation in multi-radio multi-channel wireless mesh networks,” *Ninth International Conference on Hybrid Intelligent Systems*, 2009.

[22] N. Srinvas and K. Deb, “Multi-objective function optimization using non-dominated sorting genetic algorithms,” *Evolutionary Computation*, vol. 2, no. 3, pp. 221-248, 1995.

[23] K. L. E. Law and W. C. Hung, “MAC design for interference issues in multi-channel wireless mesh networks,” in *Proc. IEEE ICC*, 2010.

[24] K. L. E. Law and W. C. Hung, "Channel control for multi-radio multichannel wireless mesh networks," in *Proc. ACM MSWiM, Vancouver*, Oct 2008.
[25] C. Y. Ku, Y. D. Lin, S. Li, and Y. C. Lai, "Utilizing multiple channels with fewer radios in wireless mesh networks," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 1, January 2011.
[26] M. Abolhasan, T. Wysocki, and E. Dutkiewicz, "A review of routing protocols for mobile ad hoc networks," *Ad Hoc Networks*, vol. 2 pp. 1–22, 2004.
[27] H. A. Mogaibel and M. Othman, "Review of routing protocols and it's metrics for wireless mesh networks," in *Proc. International Association of Computer Science and Information Technology - Spring Conference*, pp. 62 - 70, 17-20 April 2009.
[28] M. Royer and C. K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," *IEEE Personal Communication Magazine*, vol. 6, pp. 46-55, 1999.
[29] M. M. Islam. Routing Protocols for AdHoc Networks. [Online]. Available:http://www. csse.monash.edu.au/~rdp/research/ch09.pdf
[30] T. Clausen and P. Jacquet, "Optimized link state routing protocol (OLSR)," *Internet Experimental RFC 3626*, Oct 2003.
[31] Perkins and P. Bhagwat, "Highly dynamic destination sequenced distance-vector routing (DSDV) for mobile computers," in *Proc. SIGCOMM*, 1994.
[32] Perkins, E. Belding-Royer, and S. Das, "Ad hoc On-demand distance vector (AODV) routing," *Internet Experimental RFC 3561*, July 2003.
[33] Chakeres and C. Perkins, "Dynamic MANET On-demand (DYMO) routing," *Internet Standard Draft-ietf-manet-dymo-17*, Mar 2009.
[34] B. Johnson and D. A. Maltz, "Dynamic source routing in Ad Hoc wireless networks," in *Proc. Mobile Computing*, vol. 353, 1996.
[35] D. W. Kum, J. S. Park, and Y. Z. Cho, "Mobility-aware hybrid routing approach for wireless mesh networks," in *Proc. Third International Conference on Advances in Mesh Networks*, 2010.
[36] Z. J. Haas and M. R. Pearlman, "The performance of query control schemes for the zone routing protocol," *IEEE/ACM Transaction on Networking*, vol. 9, no. 4, pp. 427-38, 2001.
[37] M. Joa-Ng and I-T. Lu, "A Peer-to-Peer Zone-Based Two-Level link state routing for mobile ad hoc networks," *IEEE JSAC*, vol. 17, no.8, pp. 1415-1424, 1999.
[38] M. Lewis, R. Ogier and F. Templin, "Topology broadcast based on reverse-path forwarding routing protocol (tbrpf)," in *Internet Draft*, Work in Progress, 2003.
[39] C. E. Perkins and T. J. Watson, "Highly dynamic destination sequenced distance vector routing (DSDV) for mobile computers," in *Proc. Conference on Architectures Communications ACM*, London, UK, 1994.
[40] S. Murthy and J. J. Garcia-Luna-Aceves, "A routing protocol for packet radio networks," in *Proc. First Annual ACM International Conference on Mobile Computing and Networking*, Berkeley, CA, 1995, pp. 86–95.
[41] T. W. Chen and M. Gerla, "Global state routing: A new routing scheme for ad-hoc wireless networks," in *Proc. IEEE ICC*, 1998.
[42] M. Gerla, "Fisheye state routing protocol (FSR) for ad hoc networks," *Internet Draft*, Work in Progress, 2002.
[43] J. J. Garcia-Luna-Aceves and C. M. Spohn, "Source-tree routing in wireless networks," in *Proc. Seventh Annual International Conference on Network Protocols Toronto*, Canada, 1999, pp. 273-282.
[44] K. K. Kasera and R. Ramanathan, "A location management protocol for hierarchically organized multihop mobile wireless networks," in Proc. *IEEE 6th International Conference on Universal Personal Communications Record*, San Diego, CA, October 1997, pp. 158–162.
[45] S. Basagni, I. Chlamtac, V. R. Syrotivk, and B. A. Woodward, "A distance effect algorithm for mobility (DREAM)," in *Proc. Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking*, Dallas, TX, 1998.
[46] C. Chiang, "Routing in clustered multihop mobile wireless networks with fading channel," in *Proc. IEEE SICON*, April 1997, pp. 197–211.
[47] G. Pei, M. Gerla, X. Hong, and C. Chiang, "A wireless hierarchical routing protocol with group mobility," in *Proc. Wireless Communications and Networking*, New Orleans, 1999.
[48] K. Ramachandran, M. Buddhikot, G. Chandranmenon, S. Miller, *et al.*, "On the design and implementation of infrastructure mesh networks," in *Proc. IEEE Workshop on Wireless Mesh Networks (WiMesh)*, IEEE Press, 2005, pp. 4-15.
[49] D. S. J. De. Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," in *Proc. 9th Annual International Conference on Mobile Computing and Networking*, 2003, pp. 134–146.
[50] S. S. Ahmeda and E. A. Esseid, "Review of routing metrics and protocols for wireless mesh network," in *Proc. Second Pacific-Asia Conference on Circuits, Communications and System*, 2010.
[51] A. B. Paul and S. Nandi, "Modified optimized link state routing (M-OLSR) for wireless mesh networks," in *Proc. International Conference on Information Technology*, 2008.
[52] Johnson, D. Maltz, and J. Jetcheva, "The dynamic source routing protocol for mobile ad hoc networks," in *Internet Draft*, Work in Progress, 2002.
[53] J. Raju and J. Garcia-Luna-Aceves, "A new approach to ondemand loop-free multipath routing," in *Proc. 8th Annual IEEE International Conference on Computer Communications and Networks*, Boston, MA, October 1999, pp. 522–527.
[54] M. Royer and C.-K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," *IEEE Personal Communications*, vol. 6, no. 2, pp. 46–55, 1999.
[55] C. Toh, "A novel distributed routing protocol to support ad-hoc mobile computing" in *Proc. IEEE 15th Annual International Phoenix Conference*, 1996, pp. 480–486.
[56] R. Dube, C. Rais, K. Wang, and S. Tripathi, "Signal stability based adaptive routing (ssa) for ad hoc mobile networks," *IEEE Personal Communication*, vol. 4, no. 1, pp. 36–45, 1997.
[57] Y. B. Ko and N. H. Vaidya, "Location-aided routing (LAR) in mobile ad hoc networks," in *Proc. Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking*, Dallas, TX, 1998.
[58] M. Gunes, U. Sorges, and I. Bouazizi, "ARA–The Ant-colony based routing algorithm for MANETs," in *ICPP Workshop on Ad Hoc Networks*, August 2002, pp. 79–85.
[59] W. Su and M. Gerla, "Ipv6 flow handoff in ad-hoc wireless networks using mobility prediction," in *IEEE Global Communications Conference*, Rio de Janeiro, Brazil, December 1999, pp. 271–275.
[60] M. Jiang, J. Ji, and Y. C. Tay, "Cluster based routing protocol," in *Internet Draft*, Work in Progress, 1999
[61] Y. P. Yu, Y. H. Peng, L. Guo, and X. W. Wang, "Performance evaluation for routing protocols in wireless mesh networks," in *Proc. International Conference on Educational and Information Technology*, vol. 2, 2010, pp. 107-110.
[62] M. S. Corson and A. Ephremides, "A distributed routing algorithm for mobile wireless networks," *ACM/Baltzer Wireless Networks*, vol. 1, no. 1, pp. 61–81, 1995.
[63] V. D. Park and M. S. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks," in *Proc. INFOCOM*, April 1997.
[64] M. Joa-Ng and I.-T. Lu, "A peer-to-peer zone-based two-level link state routing for mobile ad hoc networks," *IEEE Journal*

on Selected Areas in Communications, vol. 17, no. 8, pp. 1415–1425, 1999.

[65] S. C. Woo and S. Singh, “Scalable routing protocol for ad hoc networks,” *Wireless Networks*, vol. 7, no. 5, pp. 513–529, 2001.

[66] S. Radhakrishnan, N. S. V. Rao, G. Racherla, C. N. Sekharan, and S. G. Batsell, “A routing protocol for ad hoc networks using distributed spanning trees,” in *Proc. IEEE Wireless Communications and Networking Conference*, New Orleans, 1999.

[67] N. Nikaein, H. Laboid, and C. Bonnet, “Distributed dynamic routing algorithm (ddr) for mobile ad hoc networks,” in *Proc. First Annual Workshop on Mobile Ad Hoc Networking and Computing*, MobiHOC, 2000.

[68] Z. J. Hass and R. Pearlman, “Zone routing protocol for ad-hoc networks,” in *Internet Draft*, Work in Progress, 1999.

[69] K. Ramachandran, M. Buddhikot, G. Chandranmenon, S. Miller, E. Belding-Royer, and K. Almeroth, “On the design and implementation of infrastructure mesh networks,” in *Proc. IEEE Workshop on Wireless Mesh Networks (WiMesh)’*, IEEE Press, 2005, pp. 4-15.

[70] R. Draves, J. Padhye, and B. Zill, “Routing in multi-radio, multi-hop wireless mesh networks,” in *MOBICOM*, 2004.

[71] A. A. Pirzada, M. Portmann, and J. Indulska, “Evaluation of multi-radio extensions to AODV for wireless mesh networks,” in *Proc. 4th ACM International Workshop on Mobility Management and Wireless Access (MobiWac)* , 2006, pp. 45- 51.

[72] L. J. Chen, “Research on routing protocol applied to wireless mesh networks,” in *Proc. International Conference on Communications and Mobile Computing*, 2010.

[73] A. Zakrzewska, L. Koszałka, and I. Poźniak-Koszałka, “Performance study of routing protocols for wireless mesh networks,” in *Proc. 19th International Conference on Systems Engineering*, 2008, pp. 331-336.

[74] P. N. Thai and H. Won-Joo, “Joint disjoint path routing and channel assignment in multi-radio multi-channel wireless mesh networks,” in *Proc. IEEE 68th Vehicular Technology Conference*, 2008, pp. 1-5.

[75] L. Nguyen and U. T. Nguyen, “Channel assignment for multi-cast in multi-channel multi-radio wireless mesh networks,” *Wiley Journal of Wireless Communications and Mobile Computing*, vol. 9, no. 4, pp. 557-571, 2009.

[76] D. T. M. Viet, N. H. Chau, W. Lee, and H. Q. Thuy, “Using Cross-layer heuristic and network coding to improve throughput in multi-cast wireless mesh networks,” in *Proc. International Conference on Information Networking*, 2008, pp. 1–5.

[77] X. Meng, K. Tan and Q. Zhang, “Joint routing and channel assignment in multi-radio wireless mesh networks,” in *Proc. IEEE International Conference on Communications*, vol. 1, 2006, pp. 3596-3601.

[78] H. Cheng and S. X. Yang, “Joint multi-cast routing and channel assignment in multiradio multichannel wireless mesh networks using simulated annealing,” in *Proc. 7th International Conference on Simulated Evolution And Learning*, Melbourne, Australia, 2008.

[79] C. CicconeIIi, V. Gardellin, L. Lenzini, and E. Mingozzi, “PaMeLA: A joint channel assignment and routing algorithm for multi-radio multi-channel wireless mesh networks with grid topology,” in *Proc. IEEE 6th International Conference on Mobile Adhoc and Sensor Systems*, 2009, pp. 199–207.

[80] H. Cheng and S. X. Yang, “Joint multi-cast routing and channel assignment in multiradio multichannel wireless mesh networks using tabu search,” in *Proc. Fifth International Conference on Natural Computation*, vol. 4, 2009, pp. 325–330.

[81] J. Wellons and Y. Xue, “The robust joint solution for channel assignment and routing for wireless mesh networks with time partitioning,” *Ad Hoc Networks*, 2011.

[82] M. Jahanshahi, M. Dehghan, and M. R. Meybodi, “A mathematical formulation for joint channel assignment and multi-cast routing in multi-channel multi-radio wireless mesh networks,” *Journal of Network and Computer Applications*, 2011.

[83] H. Chenga and S. X. Yang, “Joint QoSmulti-cast routing and channel assignment in multiradio multichannel wireless mesh networks using intelligent computational methods,” *Applied Soft Computing*, vol. 11, pp. 1953–1964, 2011.

[84] J. Yuan, Z. Li, W. Yu, and B. Li, “A Cross-layer optimization framework for multi-hop multi-cast in wireless mesh networks,” *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 2092-2103, November 2006.

[85] L. lannone and S. Fdida, “MRS: A simple cross-layer heuristic to improve throughput capacity in wireless mesh networks,” in *Proc. Context Conference*, Toulouse, France, October 2005.

[86] K. Li and X. Wang, “Cross-layer design of wireless mesh networks with network coding,” *IEEE Transactions on Mobile Computing*, vol. 7, no. 11, November 2008.

[87] L. You, P. Wu, Z. Pan, H. Hu, J. Song, and M. Song, “Cross-layer optimization of wireless multi-hop networks with network coding,” in *Proc. International Conference on Wireless Communications & Signal Processing*, 2009, pp.1–5.

[88] M. Alicherry and R.Bhatia, “Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks,” *IEEE Journal on Selected Areas in Communications*, vol. 24, pp. 1960–1971, 2006.

[89] A. Raniwala, K. Gopalan, and T. Chiueh, “Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks,” in *Proc. ACM SIGMOBILE*, 2004, pp. 50–65.

[90] J. Tang, G. Xue, and W. Zhang, “Interference-aware topology control and QoS routing in multi-channel wireless mesh networks,” in *Proc. ACM SIGMOBILE*, 2005, pp. 68–77.

[91] P. Kyasanur and N. H. Vaidya, “Routing and link-layer protocols for multi-channel multi-interface ad hoc wireless networks,” in *Proc. ACM SIGMOBILE*, 2006, pp. 31–43.

[92] A. Raniwala and T. Chiueh, “Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh networks,” in *Proc. IEEE InfoCom*, 2005, pp. 2223–2234.

[93] A. K. Das, H. M. K. Alazemi, R. Vijayakumar, and S. Roy, “Optimization models for fixed channel assignment in wireless mesh networks with multiple radios,” in *Proc. IEEE SECON*, 2005, pp. 463–474.

[94] G. W. Zeng, B. Ding, Y. L. Xiao, and M. Mutka, “Multi-cast algorithms for multi-channel wireless mesh networks,” in *Proc. IEEE International Conference on Network Protocols*, 2007, pp. 1–10.

[95] Z. Yin, Z. Li, and M. Chen, “A novel channel assignment algorithm for multi-cast in multi-radio wireless mesh networks,” in *Proc. IEEE ISCC*, 2007, pp. 283–288.

[96] M. Marina and S. Das, “A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks,” in *Proc. IEEE International Conference on Broadband Networks*, 2005, pp. 381–390.

[97] A. P. Subramanian, H. Gupta, and S. R. Das, “Minimum interference channel assignment in multi-radio wireless mesh networks,” in *Proc. Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, 2007, pp. 481–490.

[98] A. Raniwala and T. Chiueh, “Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh networks,” in *Proc. IEEE InfoCom*, 2005, pp. 2223–2234.

[99] A. K. Das, H. M. K Alazemi, R. Vijayakumar, and S. Roy, “Optimization models for fixed channel assignment in wireless mesh networks with multiple radios,” in *Proc. IEEE SECON*, 2005, pp. 463–474.

[100] M. Kodialam, and T. Nandagopal, “Characterizing the capacity region in multi-radio multi-channel wireless mesh networks,” in *Proc. ACM International Conference on Mobile Computing and Networking*, 2005, pp. 73–87.

[101] J. Zhang and P. Fan, “Network coding for efficient multi-cast routing in wireless ad-hoc networks,” *IEEE Transactions On Communications*, vol. 56, no. 4, April 2008.

[102] S. G. Tao, J. Q. Huang, Z. K. Yang, R. S. Youail, and W. Q. Cheng, “Routing algorithm for network coding based multi-cast,” in *Proc. International Conference on Convergence Information Technology*, 2007, pp. 2091–2095.

[103] H. Su and X. Zhang, “Modeling throughput gain of network coding in multi-channel multi-radio wireless ad hoc networks,” *IEEE Journal on Selected Areas In Communications*, vol. 27, no. 5, June 2009.

[104] M. Ahn and Y. Kim, “Network coding-based multi-cast scheduling for throughput enhancement in wireless ad hoc network,” in *Proc. International Conference on Information Networking*, 2011, pp. 188–193.

[105] H. Su and X. Zhang, “Characterizing the throughput gain of network coding in wireless ad hoc networks,” in *Proc. IEEE Military Communications Conference MILCOM* 2008, pp. 1–7.

[106] S. Katti, H. Rahul, W. J. Hu, D. Katabi, M. Medard, and Jon Crowcroft, “XORs in the Air: Practical wireless network coding,” *IEEE/ACM Transactions on Networking*, vol. 16, no. 3, June 2008.

[107] M. Yang and Y. Y. Yang, “A linear inter-session network coding scheme for multi-cast,” *Journal of Communications*, vol. 4, no. 11, December 2009.

[108] K. Xing, X. Cheng, L. Ma, and Q. Liang, “Superimposed code based channel assignment in multi-radio multi-channel wireless mesh networks,” in *Proc. ACM MOBICOM*, Montreal, QC, Canada, September 9-14, 2007, pp. 15-26.

[109] S. Zhang, S. C. Liew, and P. P. Lam, “Physical-layer network coding,” in *Proc. 12th Annual International Conference on Mobile Computing and Networking*, 2006, pp. 358–365.

[110] S. Katti, S. Gollakota, and D. Katabi, “Embracing wireless interference: Analog network coding,” in *Proc. ACM SIGCOMM*, 2007, pp. 397–408.

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