A Survey of Network Design Problems and Joint Design Approaches in Wireless Mesh Networks

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***Abstract*—Over the last decade, the paradigm of Wireless Mesh Networks (WMNs) has matured to a reasonably commonly understood one, and there has been extensive research on various areas related to WMNs such as design, deployment, protocols, performance, etc. The quantity of research being conducted in the area of wireless mesh design has dramatically increased in the past few years, due to increasing interest in this paradigm as its potential for the "last few miles", and the possibility of significant wireless services in metropolitan area networks. This recent work has focused increasingly on joint design problems, together with studies in designing specific aspects of the WMN such as routing, power control etc. in isolation. While excellent surveys and tutorials pertaining to WMNs exist in literature, the explosive growth of research in the area of specific design issues, and especially joint design, has left them behind. Our objective in this paper is to identify the fundamental WMN design problems of interference modeling, power control, topology control, link scheduling, and routing, and provide brief overviews, together with a survey of the recent research on these topics, with special stress on joint design methods. We believe this paper will fulfill an outstanding need in informing the interested student and researcher in getting familiar with this abundant recent research area, and starting research.**

***Index Terms*—Wireless Mesh Networks, Interference Modeling and Mitigation, Power Control, Topology Control, Routing, Channel Assignment, Scheduling, Joint Design Approaches, Cross-layer Design, Network Capacity and Planning.**

I. INTRODUCTION

THE WIRELESS Mesh Network (WMN) is quickly emerging as the right solution for metropolitan area networks, providing *last few miles* connectivity. There are various attractive qualities of this paradigm, which include low-cost deployment, robustness and its inheritance of useful characteristics from both the ad-hoc networking paradigm and the traditional wired infrastructure paradigm. After its original inception, the concept of mesh networking has attained a comparatively stable form, commonly understood and agreed upon by the community. This paradigm has been competently described, and research literature on the topic surveyed, by various previous work, notably [1]. We provide pointers to such surveys in Section I-C for the interested reader.

However, in the five years since [1] was published, there has been a tremendous quickening of research interest in this area,

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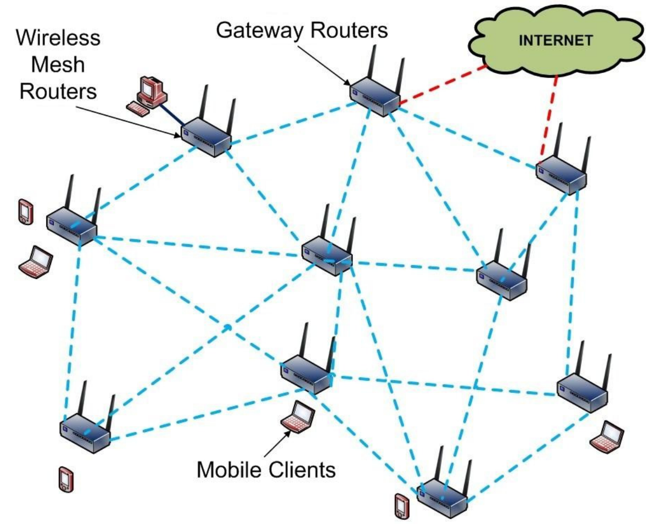

Fig. 1. Wireless mesh architecture - mesh routers, mesh clients and gateway nodes

with increased understanding of the design and deployment of such networks. One of the things that has become clear, through experimental academic testbeds and real-life deployments, is that the design problems that have been studied in isolation, such as routing, channel assignment, power control, topology control, etc., are so closely linked through the reality of wireless interference, that joint approaches to design are likely to provide much better results in practice. From the point of view of the practitioner, this is unfortunate; joint design methods are notoriously complicated, and difficult to translate into practice and maintain. In addition, different joint design studies typically make their own assumptions about the integrated framework in which design may be carried out, and there is no commonly accepted converged framework. Thus, both for the researcher and the practitioner, there is a need for a unified survey of this considerable recent literature, more than 200 papers in the last two years or so alone.

In this survey, we attempt to systematize these research efforts, and provide a review. We focus our attention on more recent efforts and joint design problems in this survey. Wherever we have considered appropriate, we have tried to provide necessary background in each topic, and then shift focus to surveying recent research. We start by providing a brief introduction to WMNs, more complete discussions can be found in previous literature. We also review recent academic research testbeds and real-world deployments and provide useful pointers. We consider this to be important background since it is experience with such testbeds that have spurred interest in joint design studies. Readers already familiar with such overview can directly skip to Section I-C where we motivate separate and joint design problems, and provide a classification and organization of the literature that is the domain of our survey in Table 1. For each category, we provide a few starting points in the literature in this table. The remaining sections of the paper survey the research on each individual topic, and are divided into two major parts. In Part I (Sections II – VIII), we survey the literature which deals with each design problem in isolation, stressing the new approaches which have come to fore in the last few years. This part is also partially tutorial in nature. Section II surveys interference modeling techniques including recent advancement of measurement based approaches. Sections III-A and III-B discuss research on power control and topology control in WMNs. This is followed by the survey of link scheduling approaches in Section IV. A variety of channel assignment and routing protocols are surveyed in Sections V and VI, respectively. Sections VII and VIII discuss network planning/deployment techniques and capacity analysis research respectively. In Part II (Sections IX – XV), we survey the joint design approaches, which consider more than one design problem in combination. We conclude in Section XVI by providing a brief overview of future research directions.

A. WMN Architecture, Characteristics and Benefits

Wireless mesh network consists of wireless mesh routers and wired/wireless clients (See Fig. 1). Wireless mesh routers communicate in multi-hop fashion forming a relatively stable network. Clients connect to these routers using a wireless or a wired link. In the most common form of WMNs, every router performs relaying of data for other mesh routers (a typical ad-hoc networking paradigm), and certain mesh routers also have the 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. This general form of WMNs can be visualized as an integration of two planes where the access plane provides connectivity to the clients while the forwarding plane relays traffic between the mesh routers. This design has become more and more popular due to the increasing usage of multiple radios in mesh routers and virtual wireless interfacing techniques.

Though WMNs inherit almost all characteristics of the more general ad-hoc network paradigm, such as decentralized design, distributed communications etc., there are a few differences. Unlike energy-constrained ad-hoc networks, mesh routers have no limitations regarding energy consumption. Also, the pattern of traffic between these routers is assumed to be fairly stable over time, more akin to typical access or campus networks, unlike sensor or tactical wireless networks. For this reason, WMN nodes can also have stable forwarding and routing roles, like more traditional infrastructure networks. In contrast, when WMNs are deployed for the purpose of short-term mission specific communication, they often act more as a tradition Mobile Ad-hoc Network (MANET). Here, the majority of the traffic flows between mesh routers (not always to the gateways as in previous case) and even clients may communicate with each other directly. This kind of architecture is referred to as a hybrid mesh [1] and is one of the promising and emerging vision for the future of WMNs.

There can be pre-planned (usually centrally controlled) as well as comparatively unstructured and incremental deployment of nodes in WMNs. In the recent past, there have been many attempts to design community wireless networks using unstructured deployment of WMNs. In such Wireless Community Networks (WCNs) [2], users own the mesh routers and participate in the network to facilitate access to other users for mutual benefit. In developed areas, the fundamental objective of such an unplanned deployment/expansion is to develop an Internet connectivity blanket for anywhere, anytime connectivity [3]. Also, WMNs deployment has been proposed as reliable and affordable access networks in underdeveloped regions. Here, the aim is to design a network as a low-cost access initiative (often by Internet Service Providers) to aid the development of communities. WMNs benefit from incremental expansion because their robustness and coverage increases as more and more mesh routers are added. These benefits of WMNs consistently motivate researchers to study their characteristics for better performance.

Two other fundamental benefits of WMNs are their ease of deployment and affordable cost. To achieve them, majority of current deployments are based on the IEEE 802.11 standard. This by no means restricts the WMNs' applicability to other standards but cheap availability of 802.11 hardware has mostly motivated this growth. Because the 802.11 software stack was originally designed for infrastructure WLANs, various modifications are necessary when using it in WMNs. Researchers are actively investigating these modifications, and the majority of efforts are directed towards design of better link layer and channel access protocols. Meanwhile, other standards like WiMAX [4] and 3G/4G are emerging and knowledge gained by research and development of WMNs over 802.11 is likely to be very useful in the future in these diverse contexts.

B. Experimental Mesh Testbeds, Real-world Deployments, Emergence of Joint Design

Simulation based studies of wireless ad-hoc networks have been long conducted and it is known that there is a significant gap between the actual measured performance and simulation results. In the last few years, increasingly cheaper and more accessible technology has allowed researchers to undertake actual testbed based evaluation of protocols. This has lead to research and development of a plethora of mesh testbeds. However, the development of such testbeds also made clear for the first time the critical importance of jointly considering traditionally isolated design problems, because the testbed designer has to make some decisions, if only by default, about the issues that are not of central interest to the research problem at hand. In simulation, it might be feasible to study the relative performance of two particular routing algorithms without making any reference to the medium access approach underneath, but an actual testbed has to use some actual MAC. Moreoever, the answer to the comparative performance question may well change depending on what MAC is used – or even details in its configuration, such as the carrier sense threshold of 802.11. Such testbeds thus spurred the quickened

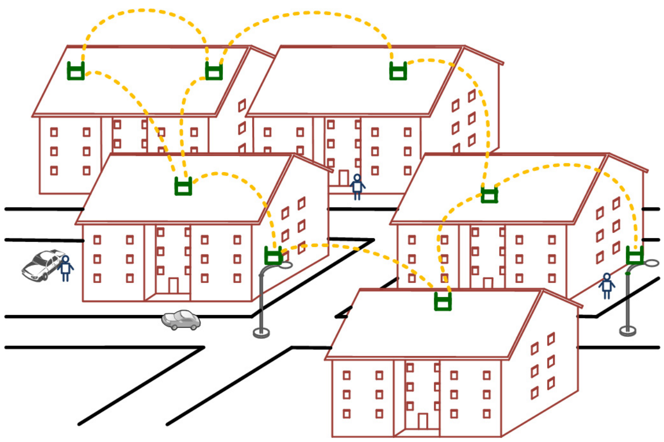

Fig. 2. Community wireless mesh network for Internet access

interest and explosive growth of the joint design research area that this survey is focused on, and in turn provide the proving ground for such research. The study of joint design in WMNs is thus also, in part, a study of research issues in WMN testbeds. Below we provide only a very brief overview to motivate our discussion on joint design; a full survey of mesh testbeds is outside the scope of this paper and merits a separate discussion.

Examples of such testbeds include MIT Roofnet [5], CuWiN [6], MeshNet [7], WiseNet [8], Mesh@Purdue [9], Broadband Wireless Networking (BWN) lab [10], SMesh [11] etc. Some testbeds like Orbit [12] and Emulab [13] provide flexible platform to other researchers who can test their methodology or protocols on them. Such efforts have given rise to many open source implementations of protocols, device drivers and network applications. Several research efforts are directed towards making community based mesh networks more and more self-organizing and cooperative [14] where every participant contributes to the network resources.

Mesh testbeds nodes are typically small single board embedded computers like Soekris boards [15] or medium capacity machines like VIA EPIA mini-ITX motherboards [16] or high capacity desktops. When using off-the-shelf hardware, wireless cards using Atheros 802.11 chipsets are often used due to their open source driver support like MadWifi [17] and recently Ath5k [18] and Ath9k [19]. Though testbed experimentations result in precise evaluation, they are often time-consuming, costly and inflexible. To overcome such issues, scaled-down, smaller transmission range versions of actual testbeds such as ScaleMesh [20] and IvyNet [21] can also be used. Sometimes a combination of simulation, emulation and real-world testbed experiments are used [22] or testbeds are deployed with advanced operating system virtualization techniques [23], [24] to improve the testbed control and management.

There is a diverse range of application scenarios for wireless mesh network deployment; this is another issue which significantly affects the perceived performance of various isolated design approaches. The fundamental objective of mesh deployment has been low-cost Internet access. Mesh networks deployed in communities spanning small or medium sized areas can be a very good business model for ISPs to provide Internet access (See Fig. 2.). TFA Rice mesh [25], Heraklion Mesh [26], Google-Meraki mesh [27] are a few of the examples of such deployments. With recent awareness about using alternate sources of energy, many of the wireless mesh routers are also designed to run with solar energy and rechargeable batteries [28]. This will certainly give rise to mesh deployments in near future where mesh routers running on solar energy can be fixed on apartment roofs or light poles, forming a mesh in neighborhood areas. Mesh networks can also serve the purpose of temporary infrastructure in disaster and emergency situations. Various control systems such as public area surveillance can also be operated using WMNs. Other applications considered for WMNs include remote medical care [29], traffic control system [30], public services [31], integration with sensor monitoring systems [32], [33]. Considering these plethora of applications, many vendors have started providing mesh based network solution for broadband Internet access. Strix systems [34], Cisco systems [35], Firetide [36], Meraki [37], Meshdynamics [38], BelAir [39], Tropos [40] and packethop [41] are some examples of commercial WMN vendors.

As indicated above, a mesh testbed requires careful design and meticulous consideration of various hardware/software aspects [42] without which performance evaluation done with the testbed can be misleading or even erroneous. Accordingly, as the deployment of testbeds proceeded both to verify research and for commercial ventures, the need for research which considered design in realistic (i.e., joint) terms became more sharply felt in the community. In turn, mesh testbeds became further necessary to verify the results of such research. We see this interaction as the main driver of research in joint design in mesh networks.

C. WMN Design Challenges

Research challenges in WMN design can be traced to network characteristics and motivations in deployment. The reason that WMNs are often seen as the last few miles network is the possibility of easy retro-fit: the coverage area of standards like WLAN can be extended further without the requirement of any specific infrastructure. Due to their mesh nature, an ideal WMN also has the properties of robustness and self-management. These imply a more ad-hoc model than the more traditional infrastructure model of access or campus area networks. Such a model poses various challenges for designers. Increasing scalability with expansion, novel MAC design, interference mitigation techniques, heterogeneity amongst standards are a few of these challenges. We motivate below the fundamental problems, and design objectives, that affect the performance of WMNs and discuss them in details. Table I summarizes this overview, and cites a few of the representative contributions in the related field. Underlined citations indicate some of the highly cited landmark contributions, while the others can be useful as introductory/tutorial papers in their respective areas of the problem. The large body of literature makes it difficult to choose representative papers; we only offer these as a possible aid to the reader who is new to the literature, with no implication of the value of the contributions of these or other papers on the same topics.

TABLE I
CLASSIFICATION OF WMN PROBLEMS, OBJECTIVES AND A FEW REPRESENTATIVE CONTRIBUTIONS

Problem	Objective	Few Representative Contributions
Interference measurement and modeling (Section II) - Tractable yet realistic estimation of interference in dynamic wireless environment	- Design of abstract interference models to aid upper layer protocol design and their comparison to actual measurements - Link and network capacity analysis	- Protocol and physical interference models [43], - scalable measurement based estimation of interference and packet delivery [44]
Power control (Section III-A) - Assigning transmission power levels to nodes having transmission requirements	- Minimizing interference - Avoiding MAC collisions for better network capacity and throughput - Power conservation (some special cases of WMNs)	- Motivations and requirements of power control mechanism [45], - uniform power assignment [46], - variable range power control [47]
Topology control (Section III-B) - Choosing or avoiding certain links in network	- Interference mitigation and reducing MAC layer collisions	- MST-based low interference topology design [48]
Link Scheduling (Section IV) - Scheduling link transmissions to achieve feasible and conflict-free transmission schedule	- Higher throughput and better spatial reuse - Efficient medium access and utilization - Fairness	- Stability property for scheduling in multi-hop networks [49], - link scheduling in protocol interference model [50] and physical interference model [51]
Channel/radio assignment (Section V) - Assigning multiple channels to single or multiple radios at nodes	- Separation in frequency domain to increase concurrent transmissions and thus throughput	- Motivations and challenges in multi-channel multi-radio mesh [52], - channel assignment using interference conflict graph based vertex or edge coloring [53], - multi-radio conflict graph based centralized channel assignment [54]
Routing (Section VI) - Choosing routing paths to satisfy end-to-end traffic demands between nodes	- Low inter-path and intra-path interference - Load balancing and hot-spot mitigation - Higher reliability and throughput	- Channel quality and diversity in multi-channel single-radio [55] and multi-channel routing [56], - opportunistic routing protocol [57], - hot-spot analysis with straight line routing [58]
Network planning and deployment (Section VII) - Topological and deployment factors, gateway placement	- Network expansion in non-cooperative environment - Load balancing with intelligent gateway placement	- Study of deployment and topological factors [59]
Performance modeling and capacity analysis (Section VIII) - Understanding best and worst case theoretical capacity	- Performance analysis and estimation of system capacity and newly developed protocols	- Best case theoretical throughput of WMNs [43], - Capacity of multi-channel WMNs [60]
Joint power control, topology control, link scheduling, routing or channel/radio assignment (Section IX, X, XI, XII, XIII, XIV, XV) - Cross layer optimization of more than one problems simultaneously	- Design and development of more informed cross-layered protocols	- Power control and scheduling [61], - routing and scheduling [62],[63], - routing and channel assignment [64], - routing, scheduling and channel assignment [65], - routing, scheduling and power control [66]

Every transmission between wireless mesh routers creates interference in its neighborhood, which is a major issue challenging the performance of WMNs. On one hand, certain high power level for transmission is necessary for successful reception at the receiver. On the other, high power transmission causes high interference and MAC layer collisions at other unintended receivers. Various attempts have been made to model the effects of interference using abstract theoretical models as well as measurement-based models. Adopting the knowledge of interference from such models, researchers have designed protocols for power control, link scheduling, routing and channel/radio assignment. Energy conservation not being an objective, power control and topology control mechanisms in WMNs mainly deal with assigning transmission power levels to nodes such that the traffic demands are satisfied with better overall throughput. The parallel objective of any such mechanism is also to reduce interference, which in turn increases the achievable network capacity.

Power control and topology control mechanisms determine the network connectivity and underlying physical layer topology. All links of such a topology can carry the traffic between the nodes, and the reception rate depends on the quality of the link. Routing strategy determines reliable and high throughput end-to-end paths between the source and destination of data. Various characteristics of links such as quality, stability and reliability play an important role in routing metric design which is used by the routing protocol. Link scheduling strategies estimate transmission conflicts between links of these routing paths using the interference model and try to achieve a conflict-free feasible transmission schedule. There are various challenges in distributed implementation of any such scheduling scheme which combines medium access, collision detection/avoidance and transmission scheduling techniques. Spatial reuse (concurrent transmissions on more than one links) can be increased when non-interfering links are scheduled in parallel using intelligent scheduling. To further mitigate the interference effects, interfering links are often separated in the frequency domain. Channel/radio assignment schemes try to arrange nearby transmissions on orthogonal or minimally overlapping channels in single or multi-radio WMNs.

It is well understood among researchers that the above mentioned problems are highly interrelated. For example, it may happen that link scheduling does not yield a high throughput schedule because of the existence of high interference links in the network. This may require the traffic of such links to be re-routed on shorter and lower interference links. This points the way to treating link scheduling and routing as a joint problem. Over the course of several years of research, it has become obvious that dealing with these interdependent problems jointly is preferable (indeed, almost unavoidable) in optimizing performance.

Previous surveys of literature largely pre-date this current body of literature. The well-known survey presented in [1] focuses on the operations and problems on layer by layer basis. Similarly, [67] and [68] survey design problems separately at each layer and provide useful insights regarding standard specific deployment issues respectively. Some of the relevant surveys are dedicated to specific design problem like multiple access protocols [69], specific techniques of improving spatial reuse [70], energy efficiency [71], [72], secure routing [73], multicast routing [74], dynamic spectrum access [75], [76], admission control [77], power control in sensor networks [78] etc. Some of the surveys like [79] and [80] cover cross-layer design proposals but they focus on single-hop infrastructure networks only. In this survey, we take a different approach where instead of surveying protocols developed at each layer, we focus on the fundamental problems and the operations like power control, link scheduling, routing etc. This approach is suitable for surveying the current research of WMN because so many of the problems and protocols deal with more than a single layer's operation. This also helps to align discussion of joint design issues and cross layering together with the discussion of individual problems.

We discuss each problem, and offer an exhaustive survey of related work, in the next few sections. A few of the most common acronyms used throughout the discussion (and indeed generally in the literature) are listed and expanded in Table II for ready reference.

PART - 1 : WMN DESIGN PROBLEMS

II. MEASURING AND MODELING THE EFFECTS OF INTERFERENCE

One fundamental requirement for designing any WMN protocol is tractable yet realistic consideration of interference. The nature and impact of interference is highly unpredictable which challenges the design of all upper-layer protocols. Researchers have proposed various ways to model the impact of interference, out of which important ones are as discussed below -

1) *Protocol Interference Model* [43]:
Communication between nodes u and v results in collision-free data reception at node v if no other node within a certain interference range from v is transmitting simultaneously. This model has been further extended to consider link layer reliability using acknowledgments in which interference range of node u is also counted for interference. This is often referred as *disk model* (or *double disk model*) where interference is assumed to be a binary phenomena developed in certain fixed distance from the source and the destination of any active link. Such Interference range of any node is often assumed to be a constant times larger than its communication range.
2) *Physical Interference Model* [43]:
Communication between nodes u and v results in collision-free data reception at node v if SINR (Signal to Interference and Noise Ratio) at node v is above a certain threshold β. If P_{vu} is the signal power received at node v from u, a packet from node u is successfully received at node v *iff*:
$$\frac{P_{vu}}{N + \Sigma_{i \in I} P_{vi}} \geq \beta \tag{1}$$
where I is a set of nodes simultaneously transmitting, N is the background noise and β is a physical layer dependent constant. The threshold based version of this SINR model was extended to a more general graded probabilistic SINR model [81] which also considers SINR lesser than the threshold and predicts the probability of successful reception.
3) *$K-$hop Interference Model* [82]:
No two links within K hops distance from each other can successfully transmit at the same time. The simplest case of such a model (with $K = 1$) is often referred as node-exclusive interference model where only restriction imposed by interference is that a node can not transmit and receive on two separate links concurrently.

The above mentioned interference models can be further generalized by representing the interference relationship of links using a *conflict graph*. In a conflict graph, every link in the network is represented as a vertex and two vertices share an edge if and only if the corresponding edges interfere with each other. Depending on interference model and its directionality characteristics, the resultant conflict graph can be undirected (double-disk model or k-hop interference model) or directed (physical interference model). All the above models assume that omni-directional antennas are used at mesh routers of WMNs. Recently, directional antennas have also been considered as a way of increasing the throughput capacity. Such antennas radiate energy assymetrically, usually predominantly in one or a few directions ("beam-forming"), which enables a transmission to reach the desired destination, while causing less interference in the rest of the network. Though directional antennas improve the overall spatial reuse, they pose various other challenges in network design due to their directionality characteristics. As an example, inclusion

TABLE II
EXPANSIONS OF COMMONLY USED ACRONYMS

Acronym of a concept or protocol	Expansion
SINR	Signal to Interference and Noise Ratio
RSSI	Received Signal Strength Indicator
TDMA	Time Division Multiple Access
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
MPLS	Multi-protocol Label Switching
RTS/CTS	Request To Send and Clear To Send
AODV	Ad hoc On-demand Distance Vector routing
DSR	Dynamic Source Routing
MIMO	Multiple Input and Multiple Output

of directional antennas require careful adaptation of the above mentioned interference models. In such a case, transmission by a node using directional antenna of beamwidth θ causes interference in a physical sector of angle θ with radius equals to its interference range [83], [84].

Modeling link quality, capacity and the effect of interference can be an extremely difficult task as the wireless environment is often a complex combination of various parameters. Some such parameters and their interaction in an outdoor mesh environment was studied in [85]. With detailed experimentation, the study concluded that most of the lossy links in such environments are loosely co-related to link distance and SNR values, but strongly related to multi-path fading of environment. Such complex interaction of these parameters probably can not be modeled by the abstract interference models described above and requires some way to model more real-time dynamic wireless conditions. Some unrealistic assumptions made by abstract wireless interference models, and the consequent mismatch of simulation results from realistic conditions, were studied in [86], [87]. Some research [88] has tried to bridge the gap between protocol and physical interference models. It shows that it is in fact possible to preserve the advantage of the binary and geometric nature of the protocol model, if results that are produced using the protocol model are revisited with suitable methodology, and the corrected interference range is utilized in the simulations.

Recently, researchers have proposed to rely on actual measurements to capture the effects of interference. If there is a way to feed the analytical models with realistic measurements like link quality, packet delivery rate etc., such models can accurately predict the interference effects. Completely depending on measurements to estimate interference might also raise a question of scalability since large number of measurements can become intractable. Realizing the importance of measuring the interference, [89] presented an initial solution to the problem of scalability. An n node network may require $O(n^4)$ measurements for measuring the pair-wise interference of all possible set of wireless links. It proposes a notion of Link Interference Ratio (LIR) which is a ratio of total throughput of links when active together to when they are active individually. Comparing LIR values on 802.11 testbed, it has been shown that most of the heuristics assumed in the literature for capturing effects of interference (including well used protocol interference model) are either too pessimistic or too optimistic about their decisions of link interference and can lead to inefficient upper layer protocols design. It then proposes an empirical methodology to approximate LIR values which requires only $O(n^2)$ actual measurements.

Such a measurement based approach can be time-consuming and does not provide analytically tractable results when used under different network settings. In contrast, [44] proposes a measurement based model where n measurements are seeded to a formulation (PHY model) which can then predict the packet delivery rate and throughput with different sets of competing senders. This PHY model modifies the traditional SINR model to use the actual measurements. Such predictions can be then used with the MAC and traffic models for estimating actual network performance. Similarly, [44] and [90] also use measurements of RSSI (Received Signal Strength Indicator - measurement of signal strength at the receiver's radio) and noise in commodity wireless cards, together with carrier sense factor values, to evaluate their effects on transmission capacity of nodes and delivery ratios of links.

With the same measurement based inputs, [91] extends the work of [44] by modeling the interference and estimating the throughput among an arbitrary number of transmitting nodes (with unicast transmissions) and realistic traffic demands. First, with the consideration of 802.11 DCF and single-hop traffic, a generic N-node Markov chain model is presented where each state represents the set of nodes transmitting simultaneously. It is then extended for a sender model that estimates throughput, and a receiver model that estimates goodput; for saturated and unsaturated traffic demands, and in a broadcast transmission scenario. In the receiver model, slot-level loss rates of the Markov chain are converted to packet-level loss rates, which might be significantly higher mainly due to the collisions with hidden terminals. Both the models are then extended for unicast transmissions which capture retransmission and back-off in the sender model, and losses in the receiver model. Similarly, [92] extends single interferer based PHY and MAC models for multiple interfering nodes and provides analytical solution for modeling link capacity in such a case.

As in the protocol interference model, interference is often assumed to be a deterministic on-off phenomenon for analytical tractability. In contrast to such a *binary* notion of interference, [93] presents a Markov chain based model for *partial* interference to derive packet transmission and corruption probabilities. The study of [94] studies *multi-way* interference, interference caused to a communication link by multiple transmitters. The authors show that even if a set of transmitters individually do not interfere with a given communication link, when they are active together they can cause significant interference to the link. This challenges the LIR approximation of [89] which considers only two transmitters at a time and points out the need of considering $k-$way interference possible from simultaneously active senders. Simulation and testbed experiments show that such multi-way interference is not wide-spread but can sometimes be significant. Improper estimation of interference can affect very basic functionality of the networking stack. The study of [95] points out a previously unrevealed impact of interference in large scale multi-hop networks. It shows that the set of discovered neighbors depends on the frequency of *hello* messages as well as the interference. The hybrid model they propose efficiently predicts the number of discovered neighbors and should be utilized to assist the *hello* protocol.

With several models and protocols depending on the measurements, it is necessary that such measurements are accurate and there exists an efficient way to collect them periodically without incurring much overhead. The study of [96] presents a distributed approach for efficient measurements in which whenever it is possible, application traffic itself is used to probe the network, instead of specialized probing packets as commonly used in many measurement schemes. This results into lower overall probing overhead. While measuring the link losses, it is also important to distinguish between different types of causes for packet losses at various levels. The study of [97] shows that packet losses might be due to MAC collisions (synchronous) or interference (asynchronous), and proposes a methodology for differentiating between the two. Such a methodology is important for accurate interpretation of the relation between measurements and causes of packet losses.

III. Power Control and Topology Control

With many wireless networks, it is often not possible to perform intelligent node deployment due to geographical constraints. In such cases, the network topology depends on power control (PC) and topology control (TC) strategies for choice of links between the nodes. Such PC/TC decisions are crucial during optimization since all design decisions like link scheduling, channel assignment, routing are affected by the underlying network topology. The terms topology control and power control are often used interchangeably in literature since both attempt to control the transmission range of nodes while trying to achieve a certain desirable property of the topology. When both control mechanisms are considered in their global system-level perspective, the power control strategies determine what power levels should be assigned to the nodes. The resultant topology is the supergraph from which a topology control mechanism chooses a subgraph that achieves a certain definite property like energy-efficiency, low interference etc. We make a distinction between the two; TC may be effected at 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 will almost invariably results in some effect on the topology, but the objective of PC may not be TC but the control of interference, or completely unrelated issues such as security, etc.

A. Power control

The problem of power control deals with assigning power levels to the nodes having transmission requirements in such a way that a particular objective is achieved, while still maintaining network connectivity as a fundamental requirement. Such an optimization objective can be lower interference, higher throughput and sometimes power conservation. Power control mechanisms proposed in the literature can be largely classified as follows.

1) Static Power Control: A static power allocation assigns power levels to the nodes that do not change frequently over time, unless there are drastic changes in the network topology. Such 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 presented in the literature can be further classified into uniform or variable range power control.

In seminal work on static power control, it was shown in [46] and [45] that throughput with all nodes operating at one common power level (COMPOW), that which is minimum required for maintaining network connectivity, is nearly optimal. It is shown that such common power level can achieve the best case capacity ($\Theta(1/\sqrt{n})$ bits/sec [43]) with optimal node deployment. It is also near optimal ($\Theta(1/\sqrt{n \log n})$ bits/sec) even in the case of random networks, without requiring any complex mechanism.

Uniform range power control protocols like COMPOW have their disadvantages, one of which is that the common power level can be very high in non-uniform clustered topologies. The COMPOW protocol was extended for variable range power control in [98]. It describes three power control protocols - CLUSTERPOW, tunneled CLUSTERPOW and MINPOW. In CLUSTERPOW, the source node for any transmission uses a power level such that no other nodes in subsequent hops will need to use a higher power level. This can be suboptimal and hence a recursive look-up mechanism is proposed in the tunneled version of the protocol. MINPOW uses the Bellman Ford algorithm with the power requirements as the cost function. Design of such protocols gave rise to many other variable range power control mechanisms which we discuss next.

In variable range power control, different nodes in the network use different power levels. Such levels are often determined based on the node locations, overall network connectivity, tolerable interference and even routing paths. It is shown in [99] that variable-range transmission power control, where every node dynamically controls the transmission power, can outperform the COMPOW approach [46] in terms of traffic carrying capacity of the network. It proposes a Minimum Spanning Tree (MST) based variable-range power control to maintain the network connectivity and increase the capacity. Specifically, it is shown that routing protocols based on such variable power levels can achieve twice the traffic carrying capacity than routing protocols based on common-range power control. An important result in [99] indicates that with variable power control, the average traffic carrying capacity remains constant even if more nodes are added to the network; this result is in contrast to the results presented in [43]. Along the same line, [47] makes the first approach to overcome the disadvantages of uniform power assignment by building a decentralized Minimum Spanning Tree (MST) based topology; the algorithm presented uses transmission power or Euclidean distance (linear with power) as the weight of an edge in the network graph, and tries to build a minimum (power) spanning tree connecting all nodes. Every node determines its one hop on-tree nodes to be its actual neighbors, and the overall topology is built by integrating the MSTs of all nodes and maintaining symmetric links. Such a topology can maintain a lower node degree which is shown to reduce interference and MAC-level collisions.

There is an interesting trade-off between *longer-hops shorter-paths* and *shorter-hops longer-paths* data transfer in multi-hop wireless networks. It is shown in [100], [101] that throughput and delay in 802.11 like networks can be optimized by using direct transmissions only. It claims that power control mechanisms should be based on per-link-minimality conditions, where nodes willing to transmit increase their power level just enough to reach the destination in a single hop. This is in sharp contrast to results in [46] in which multi-hop routing paths are chosen between source and destination. It suggests that the fully (maximally) connected topology is always the optimum topology, independent of nodal distribution, traffic pattern and offered traffic load. Authors show that in a finite ad-hoc network, COMPOW [46] does not yield maximum capacity. Under the assumption that all nodes have identical maximum power levels, it is proved that all the nodes transmitting at their maximum required power, maximizes the throughput capacity. In spite of this trade-off, it is well-known that COMPOW power level which minimizes the overall interference level in the network can achieve maximum asymptotic network capacity. Advantages of minimum or maximum power levels depend on several other factors like traffic pattern (node-to-node or node-to-gateway), network topology (uniform or clustered), etc.

Some of the previous power control and topology control mechanisms aimed to minimize the overall power consumption in traditional ad-hoc networks. With increasing outdoor deployments of wireless mesh networks, there is an opportunity to utilize alternate sources of energy, like solar energy, to operate the wireless routers. Power consumption still remains an important objective of any power assignment mechanism. The study of [102] proposes several approximation algorithms for finding a power assignment of nodes in wireless ad-hoc network such that the topology graph is k-connected (i.e., it remains connected upon removal of fewer than k vertices) and the total power utilized is the lowest. Wireless links often display unpredictable behavior and hence such fault tolerant topology holds importance in terms of survivability in WMNs. As defined in [102], an i-nearest-neighbor subgraph of G is a spanning subgraph of G in which there is an edge between two nodes u and v if and only if either u is one of the i nearest neighbor of v in G, or vice versa. A subgraph F of G is called a k-connectivity augmentation to H if $H \cup F$ is a k-connected spanning subgraph of G. The algorithm of [102] first constructs the $(k-1)$-nearest neighbor graph $G(k-1)$ from the maximum connected topology and then finds a k-connectivity augmentation F to $G(k-1)$ and outputs $G(k-1) \cup F$ with the desired property.

2) Dynamic Power Control: With dynamic power control strategies, every node 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.

Many proposed mechanisms perform the power allocation locally at every node based on the current condition of its neighbors. The PATE (Power Assignment for Throughput Enhancement) algorithm [103] is one such approach; it tries to avoid congested neighbors by choosing next-hop nodes which are less loaded. Power assignment is performed in such a way that connectivity of the network is maintained while the least congested neighbor which will create less interference to other nodes is chosen. A cost function is presented to determine the neighbors, and the corresponding required power levels to reach them. The study of [104] proposes the Power Control Multiple Access (PCMA) MAC protocol where the transmitter chooses the transmit power level based on how much interference the receiver can tolerate. It uses a separate control channel to send "busy tone signals" which advertise the tolerance levels. Similarly, Power Controlled Dual Channel (PCDC) [105] uses a separate control channel for advertising the interference tolerance. Though both PCMA and PCDC result in increased throughput due to informed decisions regarding power control, both assume wireless devices can transmit and receive at the same time on control and data channel; this requires an additional radio for each communicating device. This limitation was addressed in [106] which also proposed an improved power control protocol. POWMAC [106] uses an access window to allow for a series of RTS/CTS exchanges to take place before several data transmissions can take place concurrently. The received signal strength is then used to dynamically bind the transmission power of potentially interfering terminals in the vicinity of a receiving terminal. The required transmission power of a data packet is computed at the intended receiver, to allow for some interference margin at the receiver. This will allow multiple transmissions to take place concurrently in the neighborhood. Though POWMAC achieves concurrent transmissions using one channel only, sometimes contention may occur during the access window.

The problem of power assignment becomes even more complex when decisions must be made in a distributed fashion, with limited inforation available locally. To simplify the design, [107] proposes a feedback based fall-back power control algorithm. If a pre-determined number of transmissions are successful, the sender decrements the transmission power level until it reaches the lowest required power level without affecting the intended data rate. While decreasing power, if it encounters data loss at a certain level; it starts incrementing power level until it recovers the data rate (or reaches the highest possible power level). With the objective of power allocation in a decentralized network, [108] formulates power allocation as a problem in which interference (caused by transmissions of other users) is viewed as an external emergent condition by nodes, quantified in an "interference temperature". The approach presented tries to satisfy the interference temperature constraints and maximize a function of the sum of users' utilities.

In the IEEE 802.11 MAC standard, whenever a node wishes to transmit, it first senses the medium; if the sampled signal strength is below the carrier sense threshold, it initiates the transmission. The value of the threshold and transmit power together dictate when and at what power level a node transmits. All combinations of these two quantities may not be useful; [109] argues that the product of transmit power and carrier sense threshold should be a constant for each transmitter in the network. Based on such a mechanism, nodes transmitting at large power levels should use lower carrier sense threshold because they cause more interference to others and should be more careful before initiating their transmission. As in [110], the spatial reuse can be increased in wireless multi-hop networks such as mesh by either reducing transmission power, or increasing the carrier sense threshold. The study of [110] shows that there is a trade-off between the level of spatial reuse and the data rate that can be sustained by a transmission. It also shows that if the achievable channel rate is a continuous function of SINR, network capacity depends only on the ratio of transmit power to the carrier sense threshold. When the set of channel data rates available are discrete (as in realistic protocols like 802.11), tuning the transmission power while keeping the carrier sense threshold constant can achieve more advantages. Finally, [110] provides a localized power and rate control algorithm, where the transmitter monitors the current interference, and determines the power level accordinly. The algorithm chooses a power level in such a way that sender can sustain maximum possible data rate and the interference caused by it to other nodes is minimum. Similarly, [111] concludes that higher throughput can be achieved if area the silenced by the transmitter is reduced as much as possible, as long as it covers the interference area (containing the set of nodes that would cause collision at the receiver, if they also transimitted) of the receiver.

Multiple coverage solar powered 802.11 mesh networks with load balancing are considered in [112]; two algorithms are provided that try to dynamically activate and deactivate mesh APs based on current traffic demands.

B. Topology Control

Topology control mechanisms try to choose a certain set of links to be used out of all possible links in a network for a certain specific objective like lower power consumption, higher throughput, better fault tolerance etc. In WMNs, topology control can be used for reducing interference and thereby reducing MAC collisions. The studies of [113], [114], [115] present the CBTC (Cone-Based Topology Control) algorithm where each node finds a minimum power level at which it can reach some neighbor in every cone of degree ρ. Such a topology is shown to be preserving connectivity when $\rho < 5\pi/6$. The objective is to reduce overall power consumption with increased throughput. Though power conservation is not a major objective for power control in mesh, such an approach still holds importance as it improves on throughput and preserves network connectivity. The study of [116] formulates the topology control problem as a constrained optimization problem for (bi)connectivity while optimizing the maximum power used per node. Two centralized spanning tree based algorithms (CONNECT, BICONN-AUGMENT) and two distributed heuristics (LINT, LILT) are presented in [116] that try to achieve connected topology with minimum power utilization.

Most power/topology control approaches focus on achieving sparser topologies for higher throughput without explicitly considering the underlying issue of interference. The study of [48] disproved the common belief that sparseness (lower node degree) of topology invariably achieves lower interference. It defines network interference in terms of maximum value of *coverage* of any link uv (the number of nodes affected by communication on this link when u transmits at the power level required to reach v). It shows by examples that topology control based on nearest neighbor or graph planarity (a graph is planar if it can be drawn on a plane without any edges crossing) cannot guarantee interference-optimal topologies. Using an earlier definition of network interference, [48] proposes an MST-based centralized algorithm (LIFE - Low Interference Forest Establisher) to determine the minimum-interference connected topology. The Minimum Spanning Tree (MST) is generated by selecting links with lower coverage values which ultimately reduces the overall network interference. It also proposes a distributed variant of LIFE to find minimum interference spanner topology locally. Similarly, [117] presents algorithms to find topologies with lower *average* link/node interference.

Interference defined on the basis of link coverage as in [48] is constrained to be sender-centric, in that it does not account for receivers that may also be interfered with when a link uv is active. The study of [118] extends the definition by specifying that interference of a node v represents the number of nodes covering v with their transmission range disk when reaching their farthest neighbor. Based on this interference model, it proposes an approximation algorithm to yield minimum interference connected topology in the so-called *highway model*. Topology formation in [48], [117] account for per link interference only while building the low interference MST graph. This might lead to very high interference when end-to-end multi-hop routing paths between the node pairs are considered. The study of [119] provides a topology control algorithm where a link uv is chosen in the topology if and only if it belongs to a minimum interference path connecting any nodes w and z.

It is natural to look to topology control to address the unique characteristics of directional antennas, when these are used. The study of [120] introduces a topology control mechanism for mesh nodes with directional antennas. The k-degree spanning tree algorithm finds directions for k directional antennas at every node in such a way that node has at least k incident edges. The topology control algorithm presented in [121] and [122] try to determine power levels for nodes such that under the case of random node failures, the remaining topology retains k-connectivity with a high probability over a longer period of time.

IV. Scheduling

Link scheduling estimates the interference conflicts between the links having transmission demands (based on the interference model) and tries to achieve a conflict-free feasible transmission schedule. The first generation of scheduling algorithms ([123], [124], [125], [126], [127]) for multi-hop wireless networks were based on simplified graph models. Such algorithms mainly followed characteristics like the network topology graph and often failed to capture the issues of dynamic wireless medium such as interference. The study of [128] indicated that the graph-based scheduling does not take full interference knowledge in account while performing the link scheduling. It might be too optimistic by allowing few unintended transmissions nearby the receiver which may cause collisions or can be too pessimistic by not allowing such a transmission which can cause tolerable interference at the receiver. Compared with the physical-model type SINR-based scheduling, it achieves lower network performance. Along the same line, [129] concludes that transmission scheduling based on maximal independent set in graph-based interference model may suffer from intolerable SINR at the receivers, yielding low network capacity. Even maximizing the cardinality of the independent sets does not yield any better performance. Similarly, [130] proved with theoretical examples and experimentation that such graph-based models can undermine the achievable capacity even for simple settings of the network. They conclude the need of protocol design based on more realistic SINR-based physical interference model.

CSMA-CA and TDMA are two MAC protocols commonly used in the wireless networks. Both the protocols have their pros and cons which makes them viable choice for WMN MAC. CSMA is a simple, robust and scalable medium access technique. It does not require any time synchronization and, addition or removal of nodes from the network can be handled in distributed fashion. The Distributed Coordination Function (DCF) of 802.11 is an implementation of CSMA with binary exponential back-off. In DCF, a node wishing to transmit first senses if the medium is busy or not. If the medium is not busy, the node proceeds with the transmission but if the medium is found busy, node chooses a random back-off time and waits for that duration until the next retry. Since such carrier sense only works among one-hop neighbors, transmissions of two nodes which can not listen to each other can collide at the receiver. Such a problem is typically referred as *hidden terminal problem* and is a critical problem with 802.11 MAC. RTS/CTS (Ready to send/ Clear to send) are two messages which are used to alleviate the problem but they themselves incur higher overhead. On the other hand, TDMA does not suffer with MAC collisions in its ideal implementation because each node only transmits in its dedicated slot which does not conflict with its interfering nodes. When traffic is relatively stable (non-sporadic), TDMA can achieve maximum system capacity but there are several issued with TDMA too. Its distributed implementation is substantially difficult and requires tight time synchronization. Also, it is relatively inflexible to dynamic changes to the topology.

Since interference can be caused by many nearby nodes in mesh networks, medium access and link layer protocols are much more complicated to design. CSMA-CA based MAC protocols often suffer from lower throughput in multi-hop mesh due to its conservative design but still offers advantages of its distributed nature and standardized implementation (802.11). On the other hand, TDMA based MAC protocols are known to be more efficient due to their work-conserving nature which is better suitable for relatively stable traffic pattern of mesh backbone. The problem with TDMA based MAC protocols is that their actual implementation requires thorough engineering efforts, which is often outside the scope of research. Due to this reason, TDMA scheduling protocols can be classified into coarse-grained and fine-grained protocols. In coarse-grained TDMA protocols, emphasize is given to link scheduling with various valid assumptions of interference model, traffic demands and centralized control. To realize their potential in practice, they often have to depend on existing link layer technologies for framing, link layer acknowledgments etc. while handling medium access and transmission control at upper layers. While fine-grained TDMA protocols often handle all link layer functions at MAC layer, which makes them increasingly difficult to implement in practice. For brevity, we do not distinguish between the two kinds of TDMA protocols and discuss them together next.

A. TDMA-based Link Scheduling Protocols

Recently, CSMA-CA is shown to be not suitable for multi-hop wireless networks because of its conservative medium access and hidden/exposed terminal problems. On the other hand, TDMA based link scheduling can achieve better spatial reuse in case of WMNs where traffic demand between routers are assumed to be relatively stable. Along the first step towards designing realistic scheduling protocols, [131] provided LP formulation for node-based and edge-based spatial reuse TDMA scheduling for physical interference model. The study of [132] provided traffic controlled schedule generation algorithm but computational complexity of [131], [132] can be of a high order.

It is important to model interference relationship between links based on respective interference model before they can be scheduled. Problem of link scheduling can be represented as problem of finding maximum independent set in the conflict graph. Vertices connected to each other in the conflict graph represent those links of communication graph which interfere with each other and cannot be scheduled simultaneously. The study of [50] first designs conflict graph for protocol interference model indicating which set of links interfere with each other and cannot be scheduled together. Conflict graph in physical interference model has vertices which correspond to edges in communication graph. There is a directed edge between two vertices (edges in communication graph) whose weight indicates what fraction of the maximum permissible noise at the receiver of one link by activity on another link. This conflict graph based on interference model adds interference constraints to the LP formulation which optimizes the throughput for single source-destination pair. The LP formulation requires calculating all possible transmission schedules and it is shown to be computationally expensive.

To avoid the complex edge-based conflict graph of [50], [51] proposes a method to simplify the design of conflict graph in the physical interference model. The node-based conflict graph is designed by keeping the vertex set same as the communication graph and adding a directed edge uv between vertices u and v whose weight corresponds to the received power at v from of the signal transmitted by u. The only constraint in this case is that a node cannot transmit and receive on different links simultaneously. So, feasible schedule of links in physical interference model forms a *matching* in communication graph and should comply with SINR constraint. With non-uniform link demands and uniform random node distribution, [51] provides computationally efficient polynomial-time scheduling algorithm for which an approximation factor relative to the optimal schedule has been proved. The algorithm is not distributed and still requires a central entity to perform schedule calculation. Similar algorithm for double disk based interference model is presented in [133]. The computational complexity of spatial TDMA scheduling is known to be very high especially when using the physical interference model. In such cases, it becomes increasingly difficult to estimate or even bound the optimal scheduler performance and compares it with the proposed strategy. The study of [134] derives a column generation method using *set covering* formulation which efficiently solves the scheduling problem. The method is also used to derive tight bounds on the optimal scheduling performance which can be very useful as a benchmark for performance comparison.

To enhance the performance of TDMA, [135] considers a problem of designing minimum delay schedules via intelligent ordering of link transmissions in TDMA MAC which ensures lower node-to-gateway delays. For example, if outgoing link is assigned the slot before the incoming link in a TDMA frame then end-to-end delay may become significantly high. Instead [135] formulates the TDMA scheduling problem as a network flow problem on the conflict graph, solution to which minimizes the delay on a routing tree rooted at the gateway. First, low delay transmission ordering of links is found and then using it with the link conflict information, Bellman-ford algorithm is used to find feasible TDMA schedule in polynomial time. The study of [136] extends the work of [135] by providing a distributed scheduling algorithm. It is first shown that TDMA scheduling problem is equivalent to finding shortest paths in augmented partial conflict graph which is available at nodes based on their local information. Using distributed Bellman-ford algorithm, conflict-free and feasible schedule can then be derived.

Cross-layer optimization problem has also attracted researchers to derive resource allocation solutions for multi-hop wireless networks. Starting out, seminal work of [49] coined throughput-optimal scheduling. It showed that scheduling mechanism is throughput optimal if it maximizes queue-weighted sum of rates and also characterized maximum attainable throughput region. Scheduling policy proposed in [49] is centralized and suffers from a higher computational complexity. The study of [137] showed that relaxing scheduling component in cross-layer design can actually open up many chances for new distributed, simpler and provably efficient algorithms. The imperfect scheduling (also known as greedy scheduler or maximal weight scheduler) policy determines the schedule by choosing links in decreasing order of the traffic backlog at every node. As described in [138], such greedy maximal scheduler often performs near optimal empirically but the known bounds of its performance are still very loose. It is known that such maximal scheduler is guaranteed to achieve at least half of the maximum throughput region for node exclusive interference model [139]. Such efficiency ratio is shown to be dependent on *interference degree* of the network in [140]. It is shown that with bidirectional equal power geometric (double disk) interference model, such scheduling can achieve $1/8$ of maximum throughput region. Similarly, it was shown in [82], when $K \geq 2$, greedy maximal scheduler can achieve the efficiency ratio of $1/49$. The study of [141] showed that network topologies that satisfies local pooling condition can achieve maximum throughput in case of longest-queue first scheduling. Using this results, it was proven in [138] that greedy maximal scheduler can achieve full system capacity in tree networks under $K-$hop interference model and has efficiency ratio between $1/6$ to $1/3$ in geometric network graphs. Such an imperfect scheduling [142] has led way to many joint algorithms for scheduling [143], congestion control [144], channel assignment [145] and routing [146]. A good survey for such approaches can be found in [137].

One interesting extension of the TDMA scheduling problem is to design collision-free link scheduling of the broadcasts. Network wide broadcasting of messages is one fundamental operation in ad-hoc networks and several upper layer protocols depend on such functionality. As outlined in [147], broadcast scheduling with link interference conflicts incurs a latency which is calculated as duration between time of first broadcast and time at which all nodes receive the broadcast. The objective is to compute a broadcast schedule which requires lesser number of slots (minimum latency) and fewer numbers of retransmissions. The study of [147] first proved that minimum latency broadcast scheduling is also NP-hard and provided approximation algorithm for it. The latency of approximation algorithms was subsequently improved by [148], [149], [150], [151] and [152]. We discuss broadcast routing further in Section VI.

B. CSMA-CA Based Scheduling Protocols

Several research approaches try to modify CSMA-CA based MAC to make it suitable to multi-hop mesh networks. Such ideas hold practical importance because they can be implemented using existing available 802.11 systems. A proposed MAC named DCMA (Data-driven Cut-through Medium Access) [153] allows a packet to be forwarded from the Network Interface Card (NIC) only using MPLS like label-based forwarding. Such forwarding does not require IP route lookup or any other assistance from the forwarder's CPU. Packet's next hop is decided based on the label in RTS/ACK packet and the MAC-label table lookup in NIC. Due to combined RTS/CTS mechanism and pipeline kind of MAC-forwarding, DCMA reduces the number of channel access attempts and end-to-end latency. The study of [154] extends such the label switching based MAC design for multi-radio multi-channel WMNs. It shows that with link layer forwarding in cut-through MAC, it is possible to make channel reservations in advance for packet's next hop simultaneously while receiving them from previous hop on a different channel. It provides modified channel access/reservation mechanism for this label-switched forwarding similar to 802.11 DCF which can reduce the end-to-end delay in multi-hop communication.

The RTS/CTS mechanism of 802.11 is often disabled in WMNs because of their over-conservative nature. In such cases, hidden terminal and exposed terminal problems can increase MAC collisions. The study of [155] first proposed measurement based technique to mitigate the exposed terminal problem and improve spatial reuse. In the first phase, interference estimation technique of [89] is extended for detecting all potential exposed terminal combinations. Such information is then propagated in the network. Special control messages (RTSS – Request to Send Simultaneously, CTSS – Clear to Send Simultaneously) are then used whenever such transmissions with probable exposed terminals are encountered. This improves the overall simultaneous transmissions but requires large overhead of message transfers in the initial learning phase. The study of [156] proposes the use of location information to avoid exposed terminal problem in 802.11 MAC protocol which can lead to better spatial reuse in mesh. Similarly, [157] and [158] outline a busy-tone based solution for avoiding hidden terminal problem without interfering with data signals.

Other issues of CSMA-CA like rate control, fairness and carrier sense are also addressed for multi-hop networks. The study of [159] studies effectiveness of 802.11, 802.11e and 802.11n MACs on multi-hop mesh with different rate adaptation mechanisms. The study of [160] proposes spatial back-off algorithm which controls transmission rate and carrier sense threshold for current transmission to allow more number of other concurrent transmissions resulting into better spatial reuse. 802.11 MAC can be inherently unfair when used in multi-hop environment. Max-min models for per-flow fair bandwidth assignment to prevent such unfair MAC performance are provide in [161] and [162].

C. Other Scheduling Protocols

A scheduling mechanism is inherently fair and efficient if every node tries to transmit data depending on its backlog queue length compared to other nodes. In [163], a *distributed buffer* based design is proposed for distributed scheduling mechanism in wireless multi-hop networks. Here, transmission probability of every node is proportional to backlog of queue at its local buffer. If the arrival rate at a node is higher (often relay nodes or gateways), it gets more chance to occupy the medium for transmission. Though theoretically this may result into better fairness and higher network-wide throughput, its implementation may require modifications like busy tone, knowledge of offered load etc.

Directional antennas pose new set of challenges for link scheduling because of their different characteristics. The study of [164] provides insights about scheduling algorithm design for mesh network with directional antennas. Such a scheduling can benefit from higher transmission range and better spatial separation due to directional antennas. On the other hand, it also requires dealing with probably higher interference range, deafness and different sort of hidden terminal issues. 2-phase (2P) [157] scheduling protocol is suggested for rural area mesh networks with long point-to-point links and nodes having multiple directional antennas. In 2P, when a node switches from the transmission phase to the reception phase, its neighbors switch from the reception phase to the transmission phase and vice versa. This allows multiple receptions and transmissions possible at every node with multiple directional links (not possible by default in CSMA/CA MAC) but requires the network topology graph to be bipartite (a graph is bipartite if its vertices can be divided into two disjoint sets which are also independent sets of the graph). If the graph is not bipartite, it can be divided into several bipartite subgraphs and each such subgraph can be then assigned orthogonal channel to it as described in [165], [166]. This way 2P protocol can be used to scheduled transmission in each subgraph and transmissions between multiple such subgraph do not interfere with each other due to intelligent channel assignment.

V. Channel/Radio Assignment

To mitigate the unavoidable consequences of interference, channel assignment mechanism tries to assign different non-interfering channels to the interfering links to increase the overall spatial reuse. The studies of [52] and [167] discuss important design issues and practical challenges while designing multi-channel protocols for wireless mesh networks. As described in [53], channel assignment protocols can be broadly classified in static, dynamic and hybrid schemes. We survey each class of channel assignment protocols next.

A. Static Channel Assignment

Static channel assignment is a fixed assignment of channels to the radios of nodes which remains unchanged over the course of network operation. Such mechanisms are often less adaptive to changing wireless conditions like external interference and traffic. On the other hand, such mechanisms are simpler and do not incur channel switching delays.

In some of the earlier efforts to utilize multiple channels for network capacity enhancements, [168] proposed a multi-radio unification protocol (MUP). MUP assigns different channels to different radios of a node and this assignment is identical for all nodes of the network. A node uses best quality channel out of its all radios for communicating with its neighbor. Though it improves performance with respect to the single channel assignment, number of channels utilized in the network is still restricted by the number of radios at nodes. Channel assignment problem can be modeled as edge-coloring of the network graph and related well-known heuristics or algorithms can be applied for the solution. Along the same lines, [169] proposes a channel assignment algorithm CLICA (Connected Low Interference Channel Assignment) based on edge-coloring of the links in the connectivity graph. In the first phase of CLICA, every node greedily chooses colors for edges incident to it in a way such that the network connectivity is maintained. This choice is assisted by a weighted conflict graph so that the choice of link color minimizes the interference with conflicting links. Second phase handles multiple edges between the nodes and the unassigned radios at nodes which can be later utilized as per offered load using dynamic assignment.

Like link scheduling, conflict graph can also be used for channel assignment to incorporate interference relationship between the links. When dealing with multi-radio mesh nodes, the notion of conflict graph can be further extended to a per-radio case instead of per-node. The study of [53] provides channel assignment algorithms for multi-radio WMNs with the objective of minimizing the co-channel interference while adhering to the interface assignment constraints. It uses conflict graph representation to capture the interference based conflicts between the links. This way, channel assignment problem of network graph turns out to be a vertex coloring problem in the corresponding conflict graph. Presented centralized algorithm tries to find such a coloring with condition that number of distinct channels assigned to the links incident to a node is no more than the number of interfaces available at the node. Distributed version of the algorithm tries to resolve the same using greedy heuristics of Max-K-cut problem (problem of assigning k colors to the vertices in such a way that the number of edges with endpoints of different colors is maximal). The efficiency of optimization algorithms are proved with semi-definite programming formulation. The study of [170] shows that the link interference graphs (conflict graphs) belong to a special family of graphs called Overlapping Double-Disk (ODD) graphs. Such graphs can be created by having both endpoints of a link to possess a disk of radius half their interference range. If ODDs of two links intersect, it can be concluded that corresponding links interfere with each other. The channel assignment is performed by finding the independent sets using Polynomial-time Approximation Scheme (PTAS) in such ODD-based link interference graphs.

Changing the channel of a radio may cause several other nearby nodes to change the channels on their respective radios to maintain the symmetric links and channel dependencies. This is often referred as the *ripple effect* and it is an important design constraint addressed in the [171]. It proposes the design of logical topology from the actual physical topology while adhering to design constraints like channel dependency, ripple effect and hop count. Channel dependency constraint mentions that if multiple links are chosen in logical topology for the same radio at a node, all such links should be assigned the same channel. The choice of only a certain set of links out of the actual physical topology should also be carefully balanced to avoid long routing paths. Though there is no implicit consideration of interference, once all other constrains are formulated, actual radios are assigned channel based on the solution of logical topology. The study of [172] models the relation between channel assignment and radio assignment as binary vectors. Using link conflict graph for interference relationship, it models the achievable link rates as a function of these binary vectors. The joint problem is formulated as non-linear maximization problem, solution to which has been provided with two design schemes.

Similar to $K-$hop model of interference, [173] presents a novel edge coloring based channel assignment algorithm. The motivation is based on the observation that active links that are at distance of one hop from each other should be assigned different channel to avoid interference. This way channel assignment problem becomes Distance-1 edge coloring problem, which finds minimum number of colors such that any two active links at one hop distance are assigned different color. The problem being NP-complete, [173] provides a heuristic for solution and describes a relevant MAC scheduling protocol based on the proposed solution.

Though majority of static channel assignment algorithms depend on graph coloring, there have been few other efforts also. The study of [174] motivates the importance of component-based channel assignment in single-radio multi-channel ad-hoc networks. It proposes use of same channel for all links of a flow whenever multiple flows intersect at a node in the network. Different intersecting or contending flows may operate on different channels. Such design has merits of simplicity and lower switching delay. A combinatorial technique is used in [175], named Balanced Incomplete Block Design (BIBD), for channel assignment. Specifically in BIBD, all nodes are assigned same number of distinct channels and each channel is assigned to same number of nodes. This way the network topology turns out to be a regular graph which has a good connectivity property. The algorithm presented in [175] assigns channels such that certain connectivity is maintained and interference between same channel links are minimized.

Localized superimposed code based channel assignment algorithm is presented in [176] where nodes use *channel code* (list of primary and secondary channels) to derive interference-free channel allocation. The approach taken in [177] holds practical importance in terms of scalability and deployment where every node is equipped with two physical radios. It divides the mesh nodes into clusters, and cluster-head decides best intra-cluster channel to be used by detecting energy on every channel. Another radio at every node is dedicated for inter-cluster communication to handle the control and management messages. The study of [178] presents a ILP formulation for the channel assignment problem where the objective is to maximize total number of simultaneous transmissions on links while meeting the interference constrains. As one can see, all static policies discussed here can be used as a solution in network deployment and design phase but their inflexibility to adopt to changing conditions often require dynamic mechanisms of channel assignment which we discuss next.

B. Dynamic Channel Assignment

Such channel assignment changes dynamically based on considerations like current interference, traffic demands, power allocation etc. This results into a more challenging design problem and also adds overhead of channel switching. Such mechanisms can be further classified into per link, per packet, per time-slot based mechanisms. These channel assignment policies pose novel design problems like multi-channel hidden terminal, sporadic disconnections etc. but if carefully designed, they have the potential to achieve better system capacity.

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

The multi-channel hidden terminal problem [179] arises when channel selection is made during RTS/CTS exchange. When transmitter and receiver choose their channel for data transfer in RTS/CTS, it is possible that hidden terminal is listening on other channel. Such hidden terminal can never receive the choice of channel between sender and receiver, and may end up selecting same channel for its communication to some other node. This can result into collision at the receiver. To solve the problem of multi-channel hidden terminal, [179] proposed a multichannel MAC protocol (MMAC) which uses time synchronization between nodes in network just like 802.11 Power Saving Mode (PSM) using BECON intervals. In MMAC, in initial ATIM window all nodes tune to predefined control channel. All nodes having data to send, send ATIM message using control channel and also provides its preferred list of channels for data communication. Receivers choose a channel and sends back ATIM-ACK message. All other nodes hearing the channel choice choose their preferred channels different from it, avoiding the collision. After completion of ATIM window, actual data transfer takes place.

Sometimes it is not possible to dedicate a separate control channel due to lesser number of available orthogonal channels especially in standards like 802.11. Slotted Seeded Channel Hopping (SSCH) [180] improves on MMAC by eliminating the need of such a control channel. In SSCH, each node switches channels in every slot based on its pseudo-random channel hopping schedule. Nodes have knowledge about other's channel hopping schedule. A sender wishing to send data designs its channel schedule in such a way that in some slot it achieves an overlap with receiver schedule. Such slotted design with switching channels can also benefit from the fact that distinct links can be active on different channels avoiding interference and increasing network performance by simultaneous communication. It is shown that such a random schedule can sometimes suffer from deafness problem (*missing receiver problem*) where transmitting node does not find intended receiver during the slot of communication.

Both SSCH and MMAC protocols require tight time synchronization between the nodes in the network. To avoid this problem, [181] proposes xRDT (Extended Receiver Driven Transmission) protocol which extends RDT [182], where sender switches to well-known fixed receiver channel for data transfer. xRDT uses additional busy tone interface to mitigate multichannel hidden terminal problem which can still happen in RDT. Proposed Local Coordination-based Multi-channel MAC [181] uses control and data window similar to MMAC [179] without the need of global synchronization and busy tone interface. Senders use 802.11 based channel access mechanism in default channel to negotiate local schedules and channel usage during the control window.

CSMA-CA has been previously shown to be unfair even in single-cell infrastructure 802.11 networks. The study of [183] first points out two fundamental coordination problem which causes flow starvation and unfairness in single-channel multi-hop CSMA networks - Information Asymmetry (IA) and Flow-in-the-middle (FIM) (details in [184]). Multi-channel MAC can address these issues if designed carefully but it may itself can lead to problems like multi-channel hidden terminals or missing receiver problem [184]. Described Asynchronous Multi-channel Coordination Protocol (AMCP) uses one dedicated control channel. Nodes use the control channel to contend for preferred data channel using 802.11 DCF mechanism. Different from other previous protocols, in AMCP nodes can contend for data channels anytime without any specific synchronization. Selected data channel by sender-receiver is announced in RTS/CTS to other nodes which mark the channel to unavailable for that data communication time.

Several approaches rely on a central authority for performing the channel assignment and also try to accommodate real-time channel quality measurements. The study of [54] makes a significant contribution by developing a dynamic channel assignment algorithm which requires a centralized entity (gateway and channel assignment server). The proposed algorithm requires one radio at every mesh router to be dedicated for a common channel throughout the network. This is to maintain a connected back-bone topology, near optimal routing paths and non-interrupted flows of communication. It utilizes real-time measurements of all available channels to prioritize them based on their quality and effects of other co-located active networks (external sources of interference) on channel utilization. Based on this estimated co-channel interference, it develops a Multi-radio Conflict Graph (MCG). The MCG is build using a communication graph in which instead of every mesh router, each of its radios are presented with vertices. This way, the number of assigned channels to a node is automatically restricted by the number of radios it has. Gateway being central entity, initiates a breadth-first search for channel assignment based on the MCG and the information of channel priorities.

Because of its complexity in derivation and maintenance, only a few approaches have attempted to perform the channel assignment in distributed fashion. One of these [185] proposes a channel assignment heuristic (SAFE - Skeleton Assisted Partition Free) which assigns channels in a distributed fashion. With every node having K radios and N available channels in the network, if $N < 2K$ then every node randomly chooses K channels, leading to at least one common channel at every node. Nodes then communicate and choose different channels if their adjacent links have common channels. With $N > 2K$, SAFE finds a spanning subgraph of the network to maintain connectivity and assigns a default channel on it. As before, nodes choose a random set of channels and communicate with each other regarding their choices. Default channel is only used when other choices are not available without violating the interference limitations or the connectivity constraint.

All the approaches discussed to the point do not take traffic demands at nodes into consideration for the channel assignment. Most of the times, it is very difficult to derive a completely interference-free channel assignment solution. In such cases, if there exists a heuristic which can prioritize the links based on their importance, such a ranking of links can be helpful to perform channel assignment. The study of [186] motivated such need for traffic aware channel assignment in which partial or full information of current traffic is required. Such channel assignment ensures that nodes with high traffic demands are definitively assigned non-overlapping channels. Though presented algorithm is designed for WLANs, it can be applied to WMNs also for the high-traffic links near the gateway. Dynamic mechanisms are likely to incur higher overhead of control messages and are also more prone to ripple effect kind of real-time issues due to their fast adopting nature. The study in [187] uses routing control messages to propagate the information about channel assignment in $K-$hop neighborhood. It tries to assign non-conflicting channel to nodes during the Route Discovery and Reply processes itself to avoid any extra overhead. On the other hand, [188] defines a framework for self-healing mesh network where network reconfigures itself minimally when faults like link failure occur. For example, in the case of high interference on a particular link, it forces minimal reconfiguration of the channel assignment and avoids network-wide ripple effects. Similar mechanism has also been proposed in [189].

C. Hybrid Channel Assignment

In hybrid channel assignment 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. As shown in [190], in hybrid assignment all nodes try to assign different channel to their fixed radio. Node wishing to communicate switches its switchable radio to the channel of the fixed radio of the receiver.

IEEE 802.11 b/g standard provides 11 channels whose center frequencies are separated by 5 MHz and each channel spread around the center for 30 MHz. Though this results into only 3 non-overlapping channels, other partially overlapping channels can also be utilized for simultaneous communications if the interference caused between them is within a tolerable margin. [191] and [192] presented first analytical reasoning about how partially overlapped channels can increase the spatial reuse. In WMNs, a node assigned a partially overlapping channel (POC) can help bridge the communication between nodes with entirely non-overlapping channels. The study of [191] and [192] prove with examples that if designed carefully, POC can provide routing flexibility as well as significant throughput enhancements. The study of [193] provided an evaluation of the usefulness of POC using testbed experiments and confirmed that when utilized carefully, POCs can improve network capacity by the factor of 2 in typical 802.11 b/g case. It provides a LP formulation for achievable network capacity in multi-hop networks using POCs. It also presents an interference model which captures the effects of partial interference of POCs. The interference range of POCs is much smaller than that of non-overlapping channels. This enables more simultaneous communications leading to a better spatial reuse as described in [191], [192] and [193].

With advancements in directional antennas and cognitive radio technologies, it is important that channel assignment mechanisms intelligently accommodate their characteristics. The study of [194] uses directional antennas at every mesh router while designing mesh network. It incorporates the spatial separation provided by directional antennas in a channel assignment algorithm which improves on spatial reuse drastically. CogMesh [195] tries to address common control channel problem in cognitive radio based mesh network where spectrum access is dynamic. It tries to cluster the nodes on the basis of their detected spectrum hole and assigns it a control channel. With evolution of cognitive radio and software defined radio and their increasing usage in mesh, decisions of channel assignment and opportunistic access can become more and more complicated [196]. Because such adaptive radio technologies have capabilities to achieve true heterogeneity, their integration to mesh networks is imminent.

VI. ROUTING

Just as in any other network, finding out high throughput routing paths is a fundamental problem in WMNs. Routing metrics and protocols of wireless multi-hop networks differ from other traditional routing protocols due to dynamic and unpredictable nature of wireless medium. WMNs display relatively stable topological behavior due to lack of mobility but still underlying issues of link quality and the interference remain the same. This has motivated design and development of various new routing metrics and protocols for WMNs. First, we discuss some of the routing metrics that have been proposed for WMNs and then survey routing protocols which actually utilize them.

A. Routing Metrics for Wireless Mesh Networks

Naively utilizing the hop-count as routing metric in mesh has proven to be inefficient [197] as it does not take dynamic characteristics of wireless medium such link quality, interference etc. into consideration. As mentioned in [198], WMNs differ from other wireless ad-hoc networks in terms of their static nodes. Though inherent wireless medium is similar, the links between nodes are fairly stable and display relatively higher constant characteristics. These properties require exclusive routing metric and protocol design for WMNs. Considering the routing metrics first, [198] provides detailed explanation of characteristics that a mesh routing metric should possess. It shows that the metric should provide stable, good performance (in terms of throughput or delay), computationally efficient and loop-free routing paths. Though it has been shown that topology-dependent routing metrics are more stable in relatively static environments like mesh, many recent metrics still consider dynamic wireless conditions.

Below, we present some of metrics proposed in literature for routing in WMNs. A more detailed comparison between a very few of them can be found in [198].

1) ETX [199]: *Expected transmission count (ETX)* is the estimated number of transmissions (including retransmission) required to send a data packet over the link. In this terms, if link has a forward delivery ratio d_f (probability that data packet successfully arrives at receiver) and backward delivery ratio of d_r (probability that ACK is received by sender) then its ETX value can be defined as follows

$$ETX = \frac{1}{d_f \times d_r} \qquad (2)$$

$d_f \times d_r$ shows that packet is transmitted with success in forward direction and ACK is also successfully received in backward direction. The total ETX of a path is summation of ETX of all links on the path.

2) ETT [56]: *Expected transmission time (ETT)* improves over ETX by considering bandwidth also while assigning metric to a link. If S is the size of the packet and B is bandwidth of the link then ETT can be defined as follows

$$ETT = ETX \times \frac{S}{B} \tag{3}$$

This way, ETT of the link captures the time taken for successfully transmitting a packet on the link.

3) WCETT [56]: *Weighted cumulative ETT* improves over ETT by considering the channel diversity along the path. As different links on paths might have different channels assigned to it, it is important to capture the effect of sum of transmission times of links on every channel. Let X_j be the sum of transmission times of links on channel j as follows

$$X_j = \sum_{\textit{link i is on channel j}} ETT_i \qquad 1 \leq j \leq k \tag{4}$$

Now, WCETT can be defined as follows

$$WCETT = (1-\beta) \times \sum_{i=1}^{n} ETT_i \ + \ \beta \times \max_{1 \leq j \leq k} X_j \tag{5}$$

Thus, WCETT finds routing paths with least ETT values and highest channel diversity. WCETT is proven to be non-isotonic [198] (a metric has isotonic property if it ensures that order of weights of two paths are preserved if they are appended or prefixed by a common third path) which requires very efficient algorithms to find minimum weight paths. The study of [200] discusses how to use iterative line search technique to efficiently find WCETT based optimal or near-optimal paths using Dijsktra's algorithm.

4) MIC [201]: *Metric of interference and channel switching* improves over ETT by considering inter-flow and intra-flow interference using IRU (Interference-aware Resource Usage) and CSC (Channel Switching Cost) components of links. IRU of a link ij operating on channel c also includes its ETT and can be defined as below

$$IRU_{ij}(c) = ETT_{ij}(c) \times |N_i(c) \cup N_j(c)| \tag{6}$$

$|N_i(c) \cup N_j(c)|$ is the number of neighboring nodes interfered due to activity of a link ij on channel c. To consider intra-flow interference, every node on the routing path is assigned CSC value to it. CSC of a node x is lesser if previous link where x was receiver and next link where x is sender are on different channels. CSC value us higher if both incoming and outgoing links are on the same channel as it introduces more intra-flow interference. MIC of a routing path p can be expressed as below

$$MIC(p) = \alpha \sum_{\textit{link ij} \in p} IRU_{ij} + \sum_{\textit{node i} \in p} CSC_i \tag{7}$$

Here, $\alpha = \frac{1}{N \times min(ETT)}$ which tries to balance the load in the network.

5) MCR [202]: *Multi-channel routing* metric improves over WCETT by considering switching costs required for channel switching on different links along the path. WCETT does not capture the effect of switching delay for links active on different channels on a path. MCR adds switching delay to metric so that switching delay at every link does not take away the benefits achieved from hybrid channel assignment [190]. Let $SC(c_i)$ be the switching cost of i_{th} hop on a path, operating on channel c_i then MCR combines the effect of channel quality, diversity and switching delay as in (8).

6) WCCETT [203]: *Weighted Cumulative Consecutive ETT* also proposes a way to extend WCETT for better consideration of intra-flow interference. If we refer consecutive hops of a path which are operating on same channel as segment then WCCETT can defined as below

$$Y_j = \sum_{\textit{link i is on segment j}} ETT_i \qquad 1 \leq j \leq k \tag{9}$$

$$WCCETT = (1-\beta) \times \sum_{i=1}^{n} ETT_i \ + \ \beta \times \max_{1 \leq j \leq k} Y_j \tag{10}$$

This way, WCCETT selects a path with more channel diversity (smaller segments) compared to WCETT yielding lesser intra-flow interference.

7) iAWARE [204]: WCETT does not capture the inter-flow interference and may end up choosing congested routing paths. iAWARE uses physical interference model for calculating inter-flow interference. The study of [204] defines *Interference Ratio* (IR_l) for link l from u to v where $IR_l = min(IR_i(u), IR_i(v))$ and $IR_i(v) = \frac{SINR_i(v)}{SNR_i(v)}$. iAWARE is defined as below

$$iAWARE_l = \frac{ETT_l}{IR_l} \tag{11}$$

iAWARE of path is calculated in similar way as ETT.

8) ETOP (*Expected number of Transmissions On a Path*) [205], [206]: As mentioned in [205] and [206], ETX metric does not take into account that practically if certain number of link layer transmissions are unsuccessful, then packet is dropped and transport layer at the source node re-initiates the end-to-end transmission. In this case, if the lossy link is closer to the destination than source, most of the link transmissions from source to the lossy link are often wasted in unsuccessful end-to-end attempts. ETOP can be defined as expected number of transmissions required for delivering a packet over a path. ETOP takes into account the effect of relative position of links on path together with number of links and link quality.

$$MCR = (1-\beta) \times \sum_{i=1}^{n}(ETT_i + SC(c_i)) \ + \ \beta \times \max_{1\leq j\leq k} X_j \tag{8}$$

9) METX [207]: *Multicast ETX* (originally $C(s,d)$ [208]) captures the total expected number of transmissions required by all nodes along the source-destination path so that destination receives at least one packet successfully. It is formally defined as follows

$$METX = \sum_{l=1}^{n} \frac{1}{\prod_{i=l}^{n}(1-Perr_i)} \tag{12}$$

where l denotes l_{th} link on $n-$hop path and $Perr_l$ is the error rate of the link.

10) SPP [207]: *Success Probability Product* (originally EER in [209]) is proposed for multicast routing in WMNs. It is similar to METX and can be defined as $SPP = \prod_{l=1}^{n} d_{fl}$ where $d_{fl} = 1-Perr_l$. Considering link layer broadcast in multicast, SPP reflects the probability that destination receives the packet without error. Routing protocol should choose the path which has minimum $1/SPP$.

B. Routing Protocols

Wireless mesh networks inherit many of their characteristics from traditional ad-hoc networks. Due to lesser consideration of mobility, increasing traffic demand and certain infrastructure-like design properties, routing protocols for WMNs have required exclusive focus from researchers. Table III presents a classification of WMN routing protocols and summarizes their characteristics and objectives. We next survey research in each of these individual categories one by one in the following subsections.

1) Traditional MANET-like routing protocols: The MANET routing protocols were designed for mobile wireless nodes, intermittent links and frequently changing topologies. Such protocols often rely on flooding for route discovery and maintenance. Direct employment of such protocols is not suitable for relatively static mesh networks for various reasons.

Traditional MANET like protocols can be largely classified in reactive and proactive routing protocols. AODV [219], DSR [220] etc. are **reactive routing** protocols in which a route discovery is initiated only on demand from any source node. Links in WMNs are fairly stable over a longer period of time and likely to carry relatively stable backbone-like traffic. Flooding messages for on-demand route discovery can induce high unnecessary overhead in WMNs [198]. Also, such protocols mostly use hop-count as routing metric which is not suitable for wireless medium because it can lead to shorter yet low throughput routing paths [198], [197].

Proactive routing protocols are table-driven protocols which require flooding in case of link failure and use hop-count as primary metric for routing. They do not take link quality or any other dynamic wireless characteristics like intermediate packet losses in consideration. Many of the proactive routing protocols have been adopted or specifically designed for WMNs. As an example, OLSR [211] has recently accommodated feature for link quality sensing and it is being adapted for mesh implementations. Similarly, Babel [221] is also a proactive routing protocol based distance vector routing and utilizes link ETX values for maintaining better quality routes. Hop-by-hop forwarding (e.g. opportunistic routing) is better suited for mesh than table-driven routing protocols due to its simplicity and possible adaptation to link dynamics [198]. B.A.T.M.A.N. (Better Approach To Mobile Adhoc Networking) routing protocol [212] tries to adopt such forwarding ideology in which every node maintains logical *direction* towards the destination and accordingly chooses next-hop neighbor while routing. A useful empirical comparison of these proactive routing protocols can be found in [222].

Instead of developing new routing protocols for WMNs, many researchers have proposed modifications to the above mentioned MANET-like routing protocols. Most of such protocols try to adapt to the characteristics of WMNs such as lower mobility, stable routes etc. Also, variety of such protocols utilizes previously discussed routing metrics. Following are a few examples of such protocols:

- *AODV-ST* [210]: [210] provides AODV-ST (spanning tree) routing protocol which improves on AODV in several way to adapt to WMN characteristics. To avoid repetitive reactive route discovery with flooding, AODV-ST maintains spanning tree paths rooted at gateway from the nodes. It can incorporate high throughput metrics like ETT, ETX etc. for high performance spanning tree paths. AODV-ST also uses IP-IP encapsulation for avoiding large routing tables at relay nodes and can also perform load balancing for gateways.
- *AODV-MR* [204]: [204] presents multi radio extension for AODV protocol where each node has multiple radios and channel assignment is performed with some pre-determined static technique. AODV-MR uses iAWARE metric with bellman-ford algorithm to find efficient low interference paths. Links on such paths display low intra-flow and inter-flow interference together with good link quality.
- *ETOP-R* [205], [206]: ETOP-R routing protocol uses ETOP routing metric described earlier for finding shortest path using Dijkstra's shortest path algorithm. Practically, ETOP-R has been implemented with modified source routing protocol DSR.
- *THU-OLSR (Timer-Hit-Use OLSR)* [203]: An interval optimization algorithm is presented in [203] which adaptively adjusts control message intervals of OLSR based on the mobility. The *hello* interval and *topology control* interval of OLSR are set based on neighbor's status and

TABLE III
CLASSIFICATION OF WMN ROUTING STRATEGIES, CHARACTERISTICS, OBJECTIVES AND FEW REPRESENTATIVE CONTRIBUTIONS

Routing Strategy	Characteristics/Objective	Few Representative Contributions
MANET-like Routing (Section VI-B1)	- Reactive or Proactive - Adapt MANET routing protocols to relatively stable and high bandwidth environment of WMNs - Incorporate a WMN routing metric in existing protocol	- Proactive: AODV-ST [210] - Reactive: OLSR [211], B.A.T.M.A.N. [212]
Opportunistic Routing (Section VI-B2)	- Hop-by-hop routing - Exploit fortunate long distance receptions to make faster progress towards destination	- Ex-OR [57]
Multi-path Routing and Load Balancing (Section VI-B3)	- Maintain redundant routes to destination - Determine divergent routes to mitigate the crowded center effect - Load balancing and fault tolerance	- Multi-path routing [213], [214] - Load balancing [215]
Geographic Routing (Section VI-B4)	- Utilize location information for forwarding in large mesh networks	- Efficient geographic routing [216]
Hierarchical Routing (Section VI-B5)	- Divide network into clusters and perform routing for better scalability	- Clustering and hierarchical routing [217]
Multi-radio and multi-channel routing (Section VI-B6)	- Accommodate intra-path and inter-path interference - Consider channel assignment constraints and switching cost	- Multichannel routing [202]
Multicasting protocols (Section VI-B7)	- Adapt existing multicast mechanisms of ad-hoc networks to WMNs	- Multicasting in WMNs [207]
Broadcast Routing (Section VI-B8)	- Minimum latency broadcasting with least number of retransmissions - Adapting to multi-channel environment	- Broadcasting in multi-channel WMNs [218]

multi-point relay (MPR) selector's status. This informed values of intervals are then utilized in THU-OLSR.

- *PROC* [223]: In Progressive ROute Calculation (PROC) protocol, source node first establishes a preliminary route to destination using broadcast. Destination then initiates building of a minimum cost spanning tree to source with the nodes around the preliminary route. The source uses this optimal route for future data transfer.

2) Opportunistic Routing Protocols: As we discussed previously that traditional shortest path routing and traditional ad-hoc routing protocols may not be sufficient for mesh. Recently, opportunistic routing protocols have been proposed to exploit unpredictable nature of wireless medium. Unlike all previous approaches, opportunistic routing protocol defers the next hop selection after the packet has been transmitted. Meaning, if a packet fortunately makes it to a far distant node than expected, such useful transmissions should be fully exploited. Though there are many advantages of such mechanisms like faster progress towards the destination, it requires complex coordination between the transmitters regarding the progress of the packets. Many protocols have been developed based on such idea which we discuss below.

- *Ex-OR* [57]: An important opportunistic routing protocol was proposed in [57] which displayed its direct applicability in WMNs. In proposed routing protocol (called Ex-OR), sender broadcasts batch of packets with a list of potential forwarders in order of their chances to reach destination. The highest priority forwarder forwards the packets from its buffer each having copy of sender's estimate of highest priority node which should have received the packets. To avoid blind flooding, it maintains information about which packets have been received by the intermediate nodes. The packets which are not received and acknowledged by higher priority forwarders are forwarded by the other forwarders in the list. The process continues until the batch of packets reaches the destination.
- *SOAR* [224]: Simple Opportunistic Routing Protocol (SOAR) proposed in [224] improves on Ex-OR in certain ways and efficiently supports multiple flows in WMNs. First, it requires the nodes forwarding packets to be near the shortest path (least ETX) from source to destination to avoid packets being misdirected. Secondly, it adds a timer based low overhead distributed mechanism to coordinate between the forwarders regarding when and which packets to forward. Higher priority nodes having smaller timer values forwards first upon it expiration. Other forwarders listening to it, discards the redundant packets which avoid unnecessary flooding without any extra coordination overhead.
- *MORE* [225]: Ex-OR requires high amount of coordination between the forwarders and inherently cannot take advantage of spatial reuse. MORE [225] (MAC-independent Opportunistic Routing and Encoding) extends the Ex-OR with network coding. Here, packets are randomly mixed before forwarding to avoid the redundant packet transmissions without any need of special scheduling or coordination. Similar approaches are presented in [226], [227].
- *ROMER* [228]: Similarly, in Resilient Opportunistic Mesh Routing (ROMER) [228] protocol, a packet traverses through the nodes only *around* long-term and stable minimum cost path. These nodes build a dynamic forwarding mini-mesh of nodes on the fly. In between, each

intermediate node opportunistically selects transient high throughput links to take advantage of short-term channel variations. This way, ROMER deals with node failures and link losses, and also benefits from opportunistic high throughput routing.

3) Multi-path Routing and Load Balancing: As mentioned in [229], using traditional routing approaches and metrics, many mesh routers may end up choosing already congested routing paths to reach the gateway nodes. This can lead to low performance due to highly loaded routing paths. The study of [229] proposes a routing protocol called MMESH (Multipath Mesh), in which every node derives multiple paths to reach gateway node using the source routing. It then performs load balancing by selecting one of the least loaded paths. A large set of multi-path routing protocols are reviewed in [230].

Other multi-path routing mechanisms have been previously proposed in [231], [213] for ad-hoc networks. Interestingly, [214] claims that unless and until very large number of paths (infeasible in practice) are used in multi-path routing, single path routing performs almost as good as multi-path routing. In such cases, more routes to destination do not help much in balancing the load throughout the network. This is in line with common belief of generation of hot-spots in multi-hop wireless networks. When shortest path or straight line routing is used, most of the routing paths pass through a certain region (center of network) creating a highly congested, security prone area. Nodes in such area have to relay disproportionate amount of traffic for other nodes and often suffer from severe unfairness. Recently, [58] showed that relay load on the network mainly depends on the offered traffic pattern. When shortest path routing is used with random traffic pattern, it can give rise to different load distribution, generating hot-spot at different places in the network.

Problem of modeling the relay load of nodes in network is been addressed by a few research efforts. In uniform topologies, relay load is often modeled as a function of node's distance from the center [215], [232]. Recently, relay load of a node has also been modeled probabilistically as a function of perimeter of node's Voronoi cell [58]. Though such modeling works in uniform topologies and traffic, relay load estimation in arbitrary topologies is still an open problem. Similarly, finding ways to evenly distribute the relay load in the network is also an open research issue and is being actively investigated. Current approached for relay load balancing depends mainly on transforming Euclidean network graph on symmetric spaces like sphere or torus which do not show such *crowded center* characteristics. Many *divergent, center-avoiding* routing mechanisms described below have been proposed by researchers to try and balance the relay load among the nodes.

- *Curve-ball Routing:* [215] and [233] present an approach for load balancing in which stereographic projection is used to map the Euclidean node positions on a sphere. The routes between the source and destination are then found using great circle distance on sphere and then they are mapped back to the actual plane in network. Such routes often results in circular arc shaped forwarding which is claimed to be distributing the load in network since they intentionally avid passing through the center.
- *Outer-space Routing:* [234] proposed the concept of routing in outer space in which original network space is mapped onto a symmetric outer space (torus). The shortest routing paths between nodes in such outer space will symmetrically distribute the relay load in the entire network. Such paths are then used for routing in the original network to avoid routing via hot-spots.
- *Manhattan routing:* [235] proposed a divergent routing scheme in which source forwards the packet to an intermediate node which is near the intersection of horizontal/vertical lines passing through the source and destination.

Similarly, Several other similar load balancing mechanisms are described and analyzed in [236]. As shown in [237] and [238], such routing mechanisms display trade-off between stretch-factor of routing paths and actual load balancing.

4) Geographic Routing: The MANET routing protocols often assume the availability of location information at nodes to facilitate intelligent data forwarding. WMNs can benefit from such location information and several routing protocols are presented for such geographic routing and related issues. The study of [216] proposes an efficient geographic routing protocol where packets are forwarded towards the neighbor closest to the destination. Forwarding decisions are made on hop-by-hop basis. It proposes a link metric called Normalized Advance (NADV) which is defined as

$$NADV(n) = \frac{ADV(n)}{Cost(n)} \qquad Where \;\; ADV(n) = D(S) - D(n) \tag{13}$$

Here, $D(x)$ denotes the distance from node x to destination and $cost(n)$ can be any cost factor like packet error rate, delay etc. This way NADV reflects the amount of progress made towards the destination per unit cost.

If non-uniform topologies, geographic forwarding may result into inefficiency if an intermediate node may not find any other node towards destination. Such regions are called *routing holes* in [239], which proposes an oblivious routing scheme with fixed number of routing holes for random source destination pair traffic. Randomized routing which constructs random path around the hole is proposed in [240] where arbitrary number of such holes are considered.

Extending the current state of art in location aware routing, [241] proposes a rendezvous based routing which only requires local information about the relative direction of 1-hop neighbors at every node. Node wishing to transmit forwards the request to all four orthogonal directions and subsequent nodes forward the request in opposite direction (from which they received) until route to the destination is found. It is claimed that such routing mechanism is highly likely to find paths due to the fact that pair of orthogonal lines centered at two different points in the plane will intersect with a high probability. Similar approaches for geographic routing are presented for MANETs and sensor networks in [242], [243], [244].

In [245], authors study the problem of energy-efficient interference-based routing with respect to new flow admission in multi-hop wireless networks. The problem is first formulated as energy minimization with bandwidth constraint. It is then converted in terms of SINR constraint and matrix arithmetic is used for solving it. For any scheduling mechanism, the proposed routing algorithm utilizes SINR metric for finding shortest routes. These routes satisfy minimum SINR constraints of links for overall energy minimization in network and automatically detour from congested areas of network. The distributed version based on local information is also explained. Simulation results display low energy consumption and low flow admission blocking probability.

5) Hierarchical Routing and Clustering: Hierarchical routing has hold importance especially in mobile ad-hoc networks but its applicability to mesh networks has been limited. One possible reason for this could the fact that most of the hierarchical routing protocol presented in literature ([217], [246], [247]) assume high mobility which is rarely a case in mesh. Instead, wireless mesh show far static behavior (at least in mesh routers) and client mobility can be usually handled by typical mobility management schemes. Though efficient accommodation of clustering schemes together with channel assignment policies can explore full available capacity, designing such mechanisms with clustering is still an open issue.

6) Multi-radio/channel Routing: Such routing protocol mainly utilize routing metrics derived for multi-channel environment in suitable well-known routing protocols like AODV or DSR.

- *MCR* [202]: Multichannel routing protocol [201] uses the MCR routing metric described before with Dynamic Source Routing (DSR). Periodic information is exchanged between the nodes for announcing their fixed interface and assigned channels. This way, the resultant routing paths incur less channel switching cost and achieve best possible channel diversity to avoid intra-flow interference.
- *MCRP* [55]: Proposed multi-channel routing protocol (MCRP) assumes that nodes have only single radio which can be switched between multiple channels. In MCRP, all the nodes chosen for routing a flow are required to transmit on the same channel. Hence, channel assignment occurs on per-flow basis rather than per-link. Underlying implementation mechanism of MCRP is similar to AODV.
- *MR-LQSR* [56]: MR-LQSR uses DSR as underlying protocol with WCETT metric described above. Such a metric discovers routing paths with better channel quality and diversity. The channel assignment at nodes having multiple radios is assumed to pre-established using any mechanism.

7) Multicasting Protocols: Multicasting is an important operation in a network due to its wide use and applicability. First insights about multicasting in wireless mesh networks came in [207]. It mentions that multicast protocols for wireless multi-hop networks (e.g. On-Demand Multicast Routing Protocol (ODMRP)) use link layer broadcast and hence require changes in the unicast routing metrics. It has been shown that in case of broadcast, link quality in backward direction should not be considered because there are no ACKs involved. Also, metric product over links of a path better reveals the overall quality of the path. It then modifies existing metrics like ETX, ETT and derives METX and SPP from [208], [209] for increasing multicast throughput in WMNs.

The work of [248] proposes unicast, multicast and anycast routing mechanisms that use labeling based forwarding, motivated by the observation that nodes in WMNs are connected with other nodes in their closer proximity with a higher probability, and fulfill the doubling metric property.

8) Broadcast Routing Protocols: Broadcast is a required function in multi-hop wireless networks since many protocols depend on it for forwarding of the control messages. Broadcast latency minimization protocols were developed for single-channel, single-radio and single-rate ad-hoc networks in [147]. The study of [218] studies this problem for multi-channel, multi-radio, multi-rate mesh networks. It is shown that for such multi-channel mesh network, the broadcast latency problem is NP-hard. It proposes four heuristic based centralized algorithms to construct low latency broadcast forwarding trees in wireless mesh. Simulation results prove that channel assignment mechanisms designed for unicast may not work efficiently in broadcasting and hence broadcasting should also be considered while performing channel assignment. Similarly, [249] presents a distributed broadcast tree construction algorithm which utilizes local information only. It also takes into account the link quality and interference for broadcast protocol design. A rate selection process prior to selecting actual broadcast forwarding node is described in [250]. Using this, it claims to cover maximum number of possible nodes to receive broadcast in every stage at best possible rate. Dual association with APs by clients is also proposed for broadcast load minimization in [251].

In other routing approaches, [252] proposes a mechanism in which mobile clients associated with mesh routers, route data between themselves when the back-haul mesh routers are congested. Such mechanism can be useful when mobile clients can cooperate to build a hybrid mesh. Similarly, layer-2 routing has also been proposed which performs forwarding at link layer using MAC address. On one hand, such forwarding can be faster especially in multi-hop settings but is difficult to implement and use in heterogeneous networks. The study of [253] implemented such a layer-2 forwarding for 802.11 using Wireless Distribution System (WDS). As mentioned in [164], directional antennas can be beneficial to routing as it results into higher mesh connectivity and routing paths with lesser number of hops [254]. On the other hand, routing protocols with directional antennas should be able to coordinate transmissions in the scheduling phase and must mitigate the deafness problem.

VII. Network Planning and Deployment

In general, network planning and deployment problem deals with optimizing number and position of mesh routers and gateway nodes while meeting certain constraints like the traffic demand and coverage. Most of the upper layer protocols design assumes known network topology but the network deployment itself involves many design challenges. We next consider gateway and mesh router related design problems.

The gateway nodes in WMNs operate as integration points between the multi-hop wireless network and the wired network. Appropriate placement of such integration points is a critical factor in achievable system capacity. The gateway placement problem was investigated in [255], which tried to minimize the number of gateways while guaranteeing the overall required bandwidth. The problem is formulated as a network flow problem and max-flow min-cut based greedy algorithms are presented for various link models. Clustering based approach is presented in [256] where nodes are divided into disjoint clusters. In the next phase, a spanning tree is formed in each cluster which is rooted at the gateway node. The study of [257] presented a similar approach in which recursive searching operation greedily tries to find dominating set until the cluster radius reaches some pre-defined cluster radius. Along the same lines, [258] proved that the gateway placement problem in general WMN graph is NP-hard. It presented ILP formulation for the problem and proposes two heuristic algorithms which try to find degree based greedy dominating tree set partitioning and weight based greedy dominating tree set partitioning for efficient gateway placement. Most of the approaches for the gateway placement consider non-varying network topologies but many of WMNs in real world actually expand incrementally. To address this, [259] modeled gateway placement problem as a facility location problem. It presents gateway-placement algorithms which take into account contention at each gateway by considering routing paths in the network. Such an approach outperforms other approaches due to actual consideration of interference and load balancing at gateways. Gateway placement scheme of [260] divides the network area into a grid and chooses certain cross-points as location for gateways. The study of [261] motivates the need of multiple gateway association for clients for better load balancing, fairness and security concerns. In dynamic cross-layer association process presented in [262], clients associate to a particular mesh router not only based on channel conditions but also current AP load and routing QoS information. Problem of gateway placement is also considered jointly with routing and scheduling in [263]. Here authors provide mathematical formulation to study how these individual design problems affect the gateway placement.

Gateway placement problem assumes the positions of mesh routers are known but the optimization of number and position of mesh routers in WMNs also has attracted many researchers. The study of [264] provided an ILP formulation which selects certain candidate sites for the placement of mesh routers. It takes into consideration variety of constraints such as routing, interference, channel assignment and even rate adaptation. Similarly, [265] presented a formulation with non-linear constraints where objective is to minimize the number of mesh routers with proper channel configuration such that the traffic demand can be satisfied. The study of [266] provides a heuristic algorithm which tries to lower the cost of installation by reducing the number of mesh routers while meeting the coverage, connectivity and demand constraints. Along the same lines, [267] and [268] consider multiple objective network planning where overall interference level is also minimized along with low cost deployment and increased throughput. The proposed solution of [267] also considers fault tolerance in the case of single node failure using shared protection schemes. The same set of optimization models is further extended and compared in [269] with better load balancing of traffic across the links of the network. Some of the topological and deployment factors which can affect routing, fairness, client coverage area etc. are analytically studied in [59]. It shows that to provide 95% coverage, random node deployment requires as many as twice the number nodes required in a square or a hexagonal grid placement. A novel measurement driven deployment approach is presented in [25] where extensive measurements are taken before the actual deployment to understand the propagation characteristics of the environment. It claims that such measurement driven approach of deployment accurately predict the required resource provisioning and achievable network capacity. Provided steps of the measurement can be a useful guideline along with site survey to eliminate possible over-provisioning and disconnections.

Most of the topology control mechanisms (like [47]) assume altruist node behavior. The study of [270] shows that in a non-cooperative ubiquitous mesh deployment (similar to wireless community networks), node may act selfishly and destroy designer's goal of optimal topology. The study of [270] introduces a game-theoretic incentive-compatible framework to encourage the selfish nodes to engage in global goal of topology formation and maintenance. Addressing important issue of backbone design, [271] presents a distributed algorithm which chooses high capacity mesh nodes in backbone for relaying while [272] tries to build a backbone in non-cooperative environment with selfish nodes.

VIII. Capacity and Performance Modeling

In the seminal work of capacity modeling for wireless networks, Gupta and Kumar [43] proved that for n identical wireless nodes, throughput obtainable by each node for a randomly chosen destination is $\Theta(W/\sqrt{n \log n})$ bits/sec when nodes are located randomly and each capable of transmitting at W bits/sec. When nodes are placed optimally, with optimal traffic pattern and transmission range is optimally chosen, achievable throughput can be no more than $\Theta(W/\sqrt{n})$ bits/sec.

Followed by that [273] proved that 802.11 MAC is capable of achieving the theoretical maximum capacity of $O(1/\sqrt{n})$ per node in a large network with n nodes randomly placed and having random traffic pattern. It is also argued that one-hop node capacity is $O(n)$ in n node ad-hoc network. As more nodes are added to network, end-to-end routing paths also grow in terms of number of hops. In such case, average routing path length will be spatial diameter of the network $O(\sqrt{n})$. This way, overall throughput at each node will be approximately $O(n/\sqrt{n}) = O(1/\sqrt{n})$.

Probably, most applicable to mesh networks is the capacity analysis presented in [274]. Here, authors consider case of relays where all the nodes except source and destination relay packets with arbitrary cooperation. In such settings, when number of nodes goes to infinity the network throughput of $O(\log n)$ can be achieved. Different from traditional ad-hoc network, nodes in mesh network forward their traffic to gateways only, creating hot-spots at gateways [275]. This shows that available throughput increases with increase in number of network gateways while available capacity at each node is as low as $O(1/n)$. Per-node throughput of $O(1/n)$ is also achievable in WLANs but it is empirically observed that WMNs achieve a throughput which is often lesser than WLANs. The study of [276] showed that WMNs achieve per-node throughput of $O(1/\delta n)$ where δ is a factor dependent on hop-radius of the network and it converges to 3 for large WMNs. In similar network settings, [83] proved that upon using directional antennas, WMNs can achieve a capacity of $O(\frac{\log m}{\theta})$ when $m = 2$ and $O(\frac{\log m}{\theta^2 \log(1/\theta)})$ when $m > 2$, where m is the number of antennas on each node and θ is the beamwidth of antennas.

In arbitrary networks where node locations and traffic patterns can be controlled, each interface of capable of selecting appropriate transmission power, [60] proves that there is a loss of network capacity when the number of interfaces per node is smaller than the number of channels. While in random networks where node locations and traffic patterns are random, it is shown that one single interface is sufficient for utilizing multiple channels as long as the number of channels is scaled as $O(\log n)$ where each channel has bandwidth of W/c. The study of [277] extends this work to multi-channel networks with channel switching constraints. It considers two kinds of channel assignments with constraints namely adjacent (c, f) channel assignment and random (c, f) assignment. In adjacent (c, f) assignment, a node is assigned and can switch between randomly chosen f continuous channels out of c available channels. In such case, per-flow capacity of $\Theta(W\sqrt{\frac{f}{cn\log n}})$ can be achieved. While in random (c, f) assignment, a node can switch between fixed random subset of f channels. Per-flow capacity in such case is $O(W\sqrt{\frac{P_{rnd}}{n\log n}})$ where $P_{rnd} = 1-(1-\frac{f}{c})(1-\frac{f}{c-1})...(1-\frac{f}{c-f+1})$. The study of [278] shows that when $f = \Omega(\sqrt{c})$, random (c, f) assignment yields capacity of the same order as attainable via unconstrained switching. This opens up a new direction of designing routing and scheduling mechanism which can achieve this capacity bound.

Part - 2 : WMN Joint Design

As we discussed earlier, it is readily apparent that various individual design problems are themselves highly interdependent. As an example, when transmission power level of nodes change, the scheduling decision should be revised which may in turn require reallocation of power levels for certain nodes. Similarly, when channel assignment is performed, newer routing decisions should be made to accommodate the changes in connectivity; conversely, routing itself can help to make more intelligent decision about channel assignment. In this part, we survey the literature of several such joint design approaches where two or more design problems are dealt with jointly.

IX. Power Control and Scheduling

The scheduling algorithms take into consideration the interference relationships between the links which in turn is decided by the power assignments at nodes. The nodes transmitting at high power level creates higher interference links which reduces the overall spatial reuse when scheduled. One of the first solutions to joint problem of scheduling and power control with the objective of maximizing throughput and minimizing the power consumption was provided in [279]. The provided two-phase algorithm is centralized and need to be executed before every slot. In the first phase, algorithm determines the maximum set of nodes that can transmit in a given slot with a constraint that they should be spatially separated by at least some distance to avoid mutual interference. In the second phase, such feasible set of transmitting nodes are assigned power levels to meet their SINR constraints.

Similarly, [280] proposes a two phase distributed algorithm for power control and link scheduling in wireless networks with the objective of throughput enhancement by lowering interference. In the first phase, all links having data to send first probes the channel with some initial predetermined power by sending probe packets and measures the interference before (thermal noise) and after (interference from others) probe. With the value of increased interference, the link calculates its SNR. If its SNR is above certain threshold then it is scheduled in the coming time slot. All the links whose SNR is too low are marked undetermined and left for future scheduling. The feasible set of links run power optimization algorithm by which they optimize their power for transmission. Undetermined links still checks if they can be a part of schedule after feasible links use optimal power levels and join the schedule if they can.

A scheduling protocol should try to schedule as many links as possible in every slot of schedule to reduce the overall schedule length. The study of [61] defines the notion of *scheduling complexity*, the amount of time required to schedule a given set of requests, and uses it to analyze the capacity of wireless networks. It argues that even in case of large networks, there is no fundamental scalability problem in scheduling the transmission requests. Scheduling protocols that use uniform or linear power assignments perform much worse in terms of the scheduling complexity. Instead [61] proposes a non-linear power assignment for scheduling the links where power assigned to a link does not directly depend on its length. Such disproportional power assignment favors shorter links over the longer links and transmitter of the shorter links transmit at a higher power than what is actually needed to reach the intended receiver. In contrast, transmitting nodes of longer links still transmit at a higher required power. Based on this non-linear power assignment, a theoretical scheduling algorithm for SINR model is presented which schedules a connected set of links.

Traditional SINR-based physical model does not capture the effects of reflection, shadowing, scattering and diffraction on radio propagation. Accordingly, [281] proposes a generalized physical interference model in which received signal power at the receiver can deviate from theoretically received power by the factor of f. This way, if u transmits the data to v using a transmission power P_u, α being the path-loss exponent and d_{uv} is the distance between nodes u and v then received signal power $(P_v(u))$ at node v can range between following boundaries -

$$\frac{P_u}{f \cdot {d_{uv}}^{\alpha}} \leq P_v(u) \leq \frac{f \cdot P_u}{{d_{uv}}^{\alpha}} \quad (14)$$

Received power $P_v(u)$ should then be considered with respect to interference from other nodes at the receiver using standard physical interference model. It extends the scheduling algorithm of [61] to schedule arbitrary set of communication requests. It shows that when transmission power levels are carefully chosen, scheduling complexity of arbitrary topologies can be $O(I_{in} \cdot \log^2 n)$ with n nodes where I_{in} is a static parameter called in-interference. I_{in} is usually realized by topology control algorithms and hence topology control algorithm yielding low I_{in} achieves faster scheduling. One interesting result outlined in [281] is that topologies having unidirectional links yields lower I_{in} and therefor faster schedules compared to topologies having symmetric links. Combined algorithm of power assignment, topology control and scheduling is presented with generalized physical signal propagation model.

Continuing with distance based estimation of interference, [282] proposes a notion of *disturbance* of a link. *disturbance* of a link is the larger of maximal number of senders (or receivers) in close proximity of the sender (receiver) of the link. It proposes Low-Disturbance Scheduling Protocol (LDS) which can achieve faster schedules of length within polylogarithmic factor of network's disturbance even in worst-case low-disturbance networks. Recently, [283] proved the TDMA based link scheduling problem to be NP-complete when geometric SINR model of interference is used. In geometric SINR model, traditional SINR model is modified for the belief that the gain between two nodes is determined by the distance between them.

Rate at which a node shoves data into the network is also an important tunable variable to be considered together with power control mechanisms. The study of [284] formulates joint scheduling, power control and rate control problem as a mixed integer linear programming problem. It tries to achieve links scheduling and power assignment while meeting the data rate and peak power level constraints such that the resulting throughput is maximized. It provides a greedy heuristic for solving the optimization problem in large networks. The study of [285] presents a joint problem where TDMA scheduling, dynamic slot-by-slot power control and transmission rate control with regards to SINR are considered. The intended transmission rate is expressed in terms of packets transmitted per slot and SINR threshold is used to relate the rate with their corresponding SINR. Two separate formulations (linear number of variables based model and column generation based model) are provided for minimizing number of used time slots in derived TDMA schedule which tries to meet required SINR and traffic rate constraints.

X. Routing and Scheduling

Once the traffic demands are routed on specific routing paths, scheduling algorithm tries to achieve a conflict-free schedule for links on these routing paths. If a certain links can not be scheduled with any other link in the network, traffic on such link should be re-routed on other routing paths. Hence, several approaches try to iteratively decide on routing paths and scheduling links to achieve a better overall throughput. Firstly, [62] explored the problem of joint routing and scheduling for packet radio networks. Because of many simplified assumptions like 1-hop interference model, the solution holds a little practical importance but it provided the baseline theoretical approach towards the problem. The study of [63] proposes two centralized algorithms for joint routing and scheduling which use TDMA based contention free scheduling and utilize paths with better quality links to fulfill the bandwidth requirement. It uses $k-$hop interference model where any node within k hops of receiver should not be transmitting simultaneously. It proposes a way to estimate the value of k using the $SINR_{threshold}$ and path-loss exponent α used in SINR physical interference model as following -

$$(\sqrt[\alpha]{SINR_{threshold}} + 1) > k \geq (\sqrt[\alpha]{SINR_{threshold}}) \quad (15)$$

Heuristic to the LP problem formulation of IRMA (integrated routing MAC link scheduling) chooses routing paths based on locally available information about the MAC bandwidth and tries to avoid the congested areas. Interference relations between links is captured using a conflict graph derived for above mentioned $k-$hop interference model.

Most of the current work assumes traffic information is available in priori and based on that various scheduling and routing algorithms are designed. Such assumption in real-time network deployments can be unrealistic. Motivated by this, [286] proposes a joint traffic-oblivious routing and scheduling (TORS) algorithm which can accept any or even no traffic estimation and can still provide efficient routing paths and schedules. It provides a LP formulation with no specific assumption of interference model and utilizes the conflict graph to resolve the scheduling conflicts. The study of [287] addresses routing and scheduling problem for MIMO links as a cross-layer optimization problem. It also provides LP formulation for throughput optimization with fairness constraint for physical layer resource allocation.

The study of [288] presents a novel coordinate-based mechanism in which RSSI measurements between a node n and its neighbors are represented as a $p \times p$ square matrix and each column of such a matrix can be considered as coordinates of respective nodes in $p-$dimensional space. Such a virtual coordinate system can be used to find Euclidean distance between nodes. If such a distance is large, it can be estimated that transmission of such nodes will not interfere with each other. This way, nodes which are not in transmission range of each other can also figure out least inter-flow interference paths for routing. Once such paths are determined, scheduling scheme allows the gateway node to transmit for longer time than other mesh nodes assuming it has higher traffic demand. This gives better chances of scheduling multiple transmissions simultaneously exploiting their temporal-spatial diversity. The study of [289] formulates joint routing and scheduling problem for multi-radio multi-channel mesh and finds *concurrent transmission pattern* which is transmission rates associated with links that can be scheduled simultaneously. It uses column generation method to derive such feasible pattern in computationally efficient way which is the solution to optimization problem.

XI. Power/Topology Control and Routing

Few research attempts are made to discover the solution for routing and power control problem in conjunction. The study of [290] presents a formulation for dynamically optimizing power allocation and routing for time-varying channel characteristics and arrival rates. Capacity region of input rates are established and related joint routing and scheduling policy is presented which can stabilize the system with delay guarantees. The study of [291] considers joint topology control and routing problem for FSO (Fiber Space Optics) high speed mesh networks. FSO networks have high bandwidth, point-to-point narrow laser beam links [291]. Such networks require topology control because FSO transreciever are expensive and actual links in the topology affect performance. Provided topology control and single/multi-path routing algorithms (similar to wired optical networks) choose efficient paths so that FSO interface constraints are met and still traffic demands are satisfied.

XII. Routing and Channel Assignment

Finding routing paths with better channel diversity or channel assignment for given set of routing paths is a challenging interdependent task. The study of [292] provides one of the first centralized joint channel assignment and routing algorithm which takes into account estimated traffic demand and available channel/radio information. Algorithm recursively finds routing paths and corresponding channel assignment until the estimated traffic requirement is satisfied. Routing can be performed using hop-count based shortest path algorithm or load balancing multi-path routing. The study of [64] extends the algorithm presented in [292] for distributed design where nodes only have local information such as neighboring nodes and traffic load. Spanning tree rooted at gateway is constructed for load-balancing routing which uses hop-count, gateway link capacity or overall path capacity as metrics. Once the routing paths are found every node binds its neighbors with available radios (Neighbor-Interface Binding) and assigns channels to these interfaces (Interface-Channel Binding). Presented distributed algorithm requires local information only from $(k+1)-$neighborhood (where k is ratio of interference range to transmission range).

An interference-aware channel assignment and QoS routing algorithm is presented in [293]. In the first phase, it performs topology control using channel assignment. In this phase, it finds minimum interference channels for links such that topology is $K-$connected. In the second phase, LP formulation is provided which finds feasible low interference flow allocation on links. If such flow allocation is found then and then only new flow is admitted in the network. It provides maximum bottleneck capacity path heuristic to ensure single routing path between source and destination.

XIII. Scheduling and Channel Assignment

As discussed previously, if used intelligently partially overlapping channel can improve performance of WMNs. The study of [294] performs scheduling and channel assignment of partially overlapped channels as well as orthogonal channels with assumption of some predefined routing mechanism. It introduces channel overlapping matrix to systematically model the overlapping of the partially overlapped channels. Based on this, it presents a mutual interference model for all channels as an extension to SINR model for partially overlapping channels. Using this it proves that interference range of receiver of a link depends on channel separation of that link to its neighboring link only. Considering this interference information of channels it formulates channel assignment and scheduling as an LP formulation. The study of [295] provides heuristics for channel allocation and link scheduling for multiple partially overlapped channels (POCs) with nodes having single-radio. It points out that channel sense mechanism of CSMA/CA MAC is not suitable for POCs as it waits for the medium to be free before transmitting. In case with POCs, transmission is still possible in overlapping channels and hence proposed algorithm utilizes TDMA. It also proves that POC performs better with symmetric topologies because it achieves more spatial reuse and in high density where more contentions are probable.

A novel approach is presented in [296] which partitions the network graph into subnetworks using *local pooling*. Static channel assignment algorithm is presented for partitioning the network such that each subnetwork has a large capacity region. Like centralized approach, such partitioned network can achieve 100% throughput when using distributed scheduling algorithm for link scheduling.

XIV. Routing, Scheduling and Channel Assignment

Jointly optimizing routing, scheduling and channel assignment requires consideration of various parameters and researchers have mainly presented ILP based solution for joint optimization. The study of [297] first presented a solution to joint routing and scheduling problem in single-radio multi-channel mesh with assumption that there is sufficient number of non-interfering channels available in the network. The study of [65] extends the solution to multi-radio multi-channel mesh with limited number of available orthogonal channels. It provides ILP formulation which tries to maximize total number of flows that can be supported by the network and meet node, channel, interference and flow constraints. It then tries to balance the flow load using dynamic or static channel assignment mechanisms while greedily scheduling the links simultaneously.

Similar LP formulation for joint channel assignment, routing and scheduling problem is presented in [298]. First, the algorithm tries to find paths achieving higher throughput with flow constraints and channel interference constraints. Channel allocation algorithm then modifies this solution based on available radios and number of assigned channels to find feasible channel assignment. Such modifications may require change of routes to maintain minimum interference. Such interference-free routes and channel assignments are then scheduled in conflict-free manner. Different from [65], [298] assumes that radios can not switch between channels during operation. Important departure of this problem was studied in [299] which considers additive physical interference model (similar to geometric SINR [283]) instead of binary notion of interference. It presents two formulations for the problem -

edge-based and node-based and shows that asymmetric node-based formulation is better suited for realistic additive interference model. It then presents blossom-inequality based solution for formulation to solve generalized matching problem. The study of [300] extends LP formulation [298] of joint routing and channel assignment to use partially overlapped channels. With advancements in physical layer technologies, MIMO antennas are recently being adopted in 802.11n and 802.16 standards. Such MIMO links can send multiple data streams over its antenna elements independently. It can also eliminate interference with neighboring links if total useful number of streams and interfering streams are lesser than number of elements at receiving antenna [287]. A joint optimization problem for routing, scheduling and stream control using such MIMO links is also presented in [287].

The study of [301] deals with joint routing, scheduling and channel assignment problem with TDMA-like MAC and dynamic channel assignment. First, it proves with a simple example that multi-channel link layer and multi-path routing together can perform very well. It then proposes JMM (Joint multi-channel link layer and multi-path routing) protocol which uses receiver-based channel assignment. In each slot of the super-frame, each node either sends or receives for interference-free transmission coordination. Number of transmit and receive slots in super-frame and its pattern is dynamically learned and changed depending on traffic requirements. The proposed forwarding strategy finds two disjoint paths from nodes to the gateway while keeping broadcast overhead as low as possible. Proposed metric for finding routing path captures link quality, channel diversity, and number of hops to find minimum intra-flow and inter-flow interference routing paths. All together, JMM achieves better performance by using multiple channels and paths together with timely coordinated transmissions.

XV. Routing, Scheduling and Power Control

Routing, scheduling and power control decisions are highly interrelated and should be considered together for optimization. The study of [302] presents one of the first solutions to this joint problem for multi-hop wireless networks. In the first phase, link scheduling and power control is performed with the objective of minimizing total power consumption. Feasible set of links and corresponding power levels are found with the constraints that each link has an average data rate no less than some given value and every node transmits at its pick power level in its assigned slot. To reduce the complexity of solution with large number of links, hierarchical scheduling and power control is performed on clusters [303]. These decisions are integrated in second phase to determine routing paths. Routing facilitates the required data rates on each link based on source-destination traffic demand matrix. Similarly, [304] presents formulation for joint optimization problem with objective of minimizing power consumption with non-linear constraints of routing and scheduling. It provides solution using 3-approximation algorithm which yields set of routes, schedule and transmission powers. The study of [305] presents similar solution but there are no assumptions on prior knowledge of traffic matrix. Instead, it assumes that traffic matrix always lies in a given polytope which is derived using ingress and egress capacity of nodes.

Along similar lines, [306] presents a joint scheduling, power control and routing algorithm for TDMA-based wireless ad-hoc networks. In the first part, it is proved that performing scheduling together with power control yields better throughput and lower delay than doing scheduling separately. Centralized algorithm is presented where links are added to feasible schedule or removed based on scheduling rules (queue length at node, SINR constraint and disjoint endpoints) and then per-link power control is performed. Running this algorithm without consideration of routing may cause congestion and bandwidth request may not be always satisfied. So, routing is integrated with scheduling and power control in the second part. Routing uses Bellman-ford shortest path algorithm on metric that captures effect of traffic congestion and link conflicts. Simulation results show performing routing, scheduling and power control can yield better network performance.

Interesting trade-off of *larger-range lesser-hops* and *shorter-range more-hops* is pointed out in [133]. It shows that if high power transmissions are used, it gives rise long high interference links. Such links can not be scheduled with other links but the data reaches the destination in fewer hops with lesser delay. Instead, if low power transmissions are used, data reaches the destination via many hops but all such shorter links can be scheduled with more and more other links. It is an open question whether any of these two mechanisms perform better in terms of throughput and delay. The study of [133] introduces *loner links*, the links which can not be scheduled with any other link in the network due to its high interference characteristics. Traffic on such links should be re-routed via shorter low interference links. Analytical characterization of loner links is also presented for square or circular network areas.

XVI. Conclusion

There has been an impressive amount of research effort concentrating on design of wireless multi-hop mesh networks in the last few years. Both the research community, and commercial vendors, are attracted to the multi-hop paradigm because of its simplicity, robustness, ease of setup/maintenance and self-organizing nature. Factors like support for heterogeneity, opportunity for using off-the-shelf hardware, affordable community driven infrastructure and increasing open-source software development have given tremendous rise to WMNs development and research. From a survey of the research, it seems clear that researchers recognize the importance of addressing theoretical issues in mesh design under realistic conditions of commodity hardware, protocols, and joint design. This significantly increases the usability of research results in practical applications.

Research is far from complete in addressing the needs of such practical application. Some of the more pressing open research issues include efficient MAC design, scalability with incremental expansion of the network, and security. WMNs have the potential to be integrated with other networks like sensor network, vehicular networks, delay tolerant networks with mechanical backhaul (data ferried by buses, trains etc.)

and WiMAX based infrastructure networks. The integration methodology and related application development is also an open research issue. Further importance is lent to this by continuing development and improvement in link layer and physical layer techniques. There is a clear need of continuing research on many problems in this area, especially on the recently emerged approaches using joint design that was the topic of this survey.

Considering all envisaged applications, wireless mesh networks appear to have unprecedented and as yet unrealized potential. With the numerous recent research efforts, they are likely to see great growth in both commercial development and research.

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