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A SURVEY OF COMBINED NETWORK DESIGNS IN WIRELESS MESH NETWORKS

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***Abstract*—Over the last decade, the model of Wireless Mesh Networks (WMNs) has improved a lot, 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 model 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 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 combined design methods.**

***Index Terms*—Wireless Mesh Networks, Power Control, Topology Control, Routing, Channel Assignment, Scheduling**

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 model, which include low-cost deployment, robustness and its inheritance of useful characteristics from both the ad-hoc networking model and the traditional wired infrastructure model. After its original inception, the concept of mesh networking has attained a comparatively stable form, commonly understood and agreed upon by the community. This model has been described, and research literature on the topic surveyed, by various previous work [1]. 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.

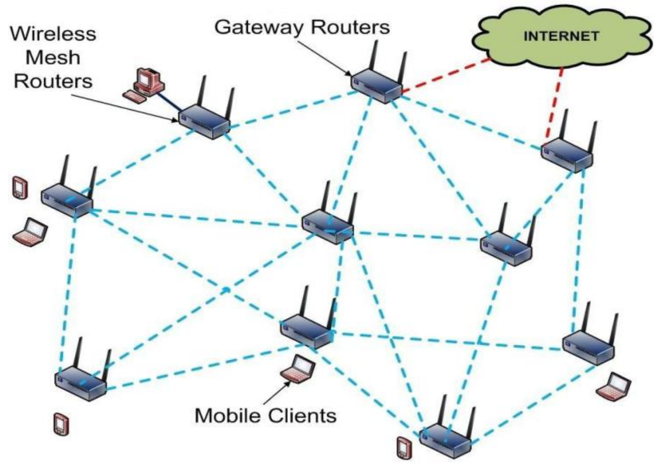

Fig. 1. Wireless mesh architecture - mesh routers, mesh clients and gateway nodes

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 model), 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 model, 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 similar 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 modi-fications 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 many of mesh testbeds.

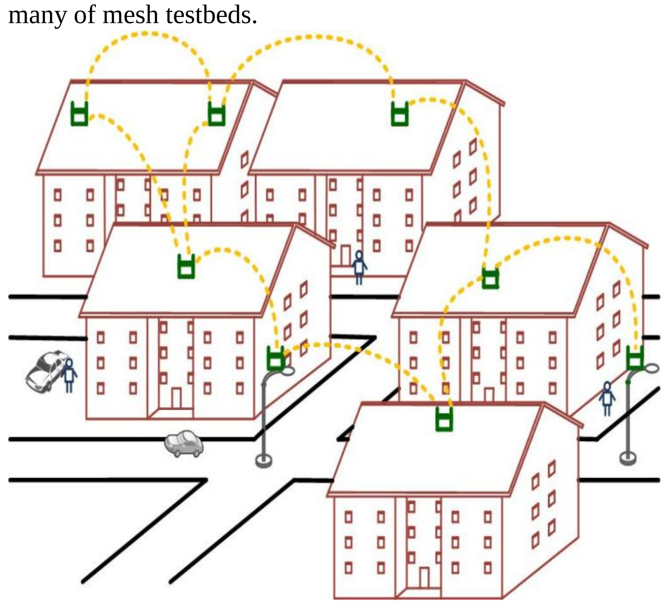

Fig. 2. Community wireless mesh network for Internet access

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, Heraklion Mesh, Google-Meraki mesh 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. 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 neighbourhood 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, traffic control system, public services, integration with sensor monitoring systems. Considering these plethora of applications, many vendors have started providing mesh based network solution for broadband Internet access. Strix systems, Cisco systems, Firetide, Meraki, Meshdynamics, BelAir, Tropos and packethop are some examples of commercial WMN vendors.

As indicated above, a mesh testbed requires careful design and meticulous consideration of various hardware/software aspects 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.

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 proto-col. 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 imple-mentation of any such scheduling scheme which combines medium access, collision detection/avoidance and transmission scheduling techniques. 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, [5] and [6] 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, specific techniques of improving spatial reuse, energy efficiency, secure routing, multicast routing, dynamic spectrum access, admission control, power control in sensor networks, etc. Some of the surveys like [7] and [8] 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.

II. WMN COMBINE DESIGNS

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.

A. POWER CONTROL AND SCHEDULING

The scheduling algorithms take into consideration the in-terference relationships between the links which in turn is de-cided by the power assignments at nodes. The nodes transmit-ting 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 [9]. 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, [10] 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 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 [11] 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 [11] 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.

B. ROUTING AND SCHEDULING

Once 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, [12] 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 [13] 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 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, [14] 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 [15] 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.

C. 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 [16] 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 [17] 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 [18]. 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.

D. 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 [19] 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 [14] extends the algorithm presented in [20] 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 [21]. In the first phase, it performs topology control using channel assignment. In this phase, it finds minimum interference channels for links such that topol-ogy 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.

E. SCHEDULING AND CHANNEL ASSIGNMENT

As discussed previously, if used intelligently partially over-lapping channel can improve performance of WMNs. The study of [22] performs scheduling and channel assignment of partially overlapped channels as well as orthogonal chan-nels 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 [23] 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.

F. 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 [24] 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 [25] 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 [26]. 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 [25], [26] assumes that radios cannot switch between channels during operation. Important departure of this problem was studied in [27] which considers additive physical interference model 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 [28] extends LP formulation [26] 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 neighbouring links if total useful number of streams and interfering streams are lesser than number of elements at receiving antenna [29]. A joint optimization problem for routing, scheduling and stream control using such MIMO links is also presented in [29].

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 [30] 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 [31]. 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, [32] 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 [33] 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.

Interesting trade-off of *larger-range lesser-hops* and *shorter-range more-hops* is pointed out in [34]. 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 [34] 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 model 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 networks, vehicular networks, delay tolerant networks 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 need of continuing research on many problems in this area, especially on the recently emerged approaches using combined 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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