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Survey on Mac Layer Solutions for Scalable Wireless Mesh Networks

A.B Nataraju
Research Scholar, Jain University, Bangalore, India
Assistant Professor, Department of ECE,
Acharya Institute of Technology, Bangalore, India
nataraju.ab@gmail.com

Dr. H.D Maheshappa
Principal, Acharya Institute of Technology, Bangalore, India
maheshappahd@acharya.ac.in / hdmappa@gmail.com

ABSTRACT

Wireless Mesh Networks (WMNs) have been considered as a key technology for next-generation wireless networking. WMNs are undergoing rapid progress and inspiring numerous applications, because of the simplicity and extensibility when compared to other wireless networks. However, many technical issues still exist in the field of wireless networks. In order to provide a better understanding of the research challenges of WMNs, this article presents a detailed study of current state-of-the-art MAC protocols and algorithms for scalable WMNs. Open research issues related to scalability are also discussed.

KEYWORDS- WIRELESS MESH NETWORKS, 802.11S, SCALABILITY, MR-MC, LINK SCHEDULING

1. INTRODUCTION

WMNs are one of the emerging technologies of the next generation networks (NGN), and are expected to address the internet provision to users with short setup time, low cost, available anytime, anywhere. A WMN [1][2]is a communications network made up of radio nodes organized in a mesh topology. WMN's capability for self-healing, self-organization significantly reduces the complexity of network deployment and maintenance, and thus, requires minimal upfront cost. It consists of mesh clients (MC), mesh routers (MR) and gateways (GW). The MCs are often laptops, mobile cell phones and other wireless devices while the mesh routers forward traffic to and from the gateways, which may / may not connect to the Internet. The coverage area of set of radio nodes working as a single network is often addressed a mesh cloud. Access to the mesh cloud is dependent on the radio nodes working in harmony with each other to create a radio network. Each node in any WMN operates not only as a host but also as a router, forwarding packets on behalf of other neighboring nodes that may not be within direct wireless transmission range of their destinations. A mesh network is reliable and offers high availability. When a node can no longer operate as usual, the rest of the nodes can still continue to communicate with each other, directly or through one or more intermediate nodes. Wireless mesh networks can be implemented with various wireless technologies including IEEE.802.11 (WLAN), IEEE.802.15 (WPAN), and IEEE.802.16 (WMAN), cellular technologies or combinations of these technologies. The integration of WMNs with other networks can be accomplished through the gateway and bridging functions in the MRs. Mesh clients can be either stationary or mobile, and can form a mesh of clients among themselves and with mesh routers. WMNs are expected to resolve the limitations and significantly improve the performance when compared to ad hoc networks, wireless local area networks (WLANs), wireless personal area networks (WPANs), or wireless metropolitan area networks (WMANs). Being a broadband wireless network of the future, it is still facing a lot of technical and non-technical issues which are prohibiting it from the world wide deployment and acceptance.

Some of the widely used applications of WMNs are (a) Broadband home networking, (b) Community and neighborhood networking, (c) Enterprise networking, (d) Transportation systems, (e) Building automation, (f) Health and medical systems, (g) Security surveillance systems.

The rest of the paper is organized as follows: Sec-2 gives brief architectural details of WMNs; Sec-3 provides a set of characteristics and challenges in designing a WMN; Sec-4 provides the brief review of existing literature on scalable WMNs; Sec-5 draws the inferences from the literature survey and also list out open issues related to scalable WMNs.

2. ARCHITECTURE OF WIRELESS MESH NETWORKS

The major components of WMN are MC, MR, and GWs. A simple depiction of the WMN architecture is presented in the *Figure 1*, which is intended to use *WMN as backbone* network without any wired connections (wireless replacement for the existing wired internet). *Figure 2* depicts the mesh clients forming a simple adhoc network without the support of any infrastructure with an arbitrary number of mesh users, which is addressed as *client WMNs*. *Figure 3* depicts the combination of client mesh networks and set of MRs and GWs to support client WMNs to communicate with existing wired / wireless infrastructures. Thus these networks are addressed as *Hybrid WMNs*. Even though WMNs have very short deployment time and minimum upfront deployment cost, they are faced with many technical and operational constraints. The characteristics / features and challenges in designing WMNs are elaborated in the following sections.

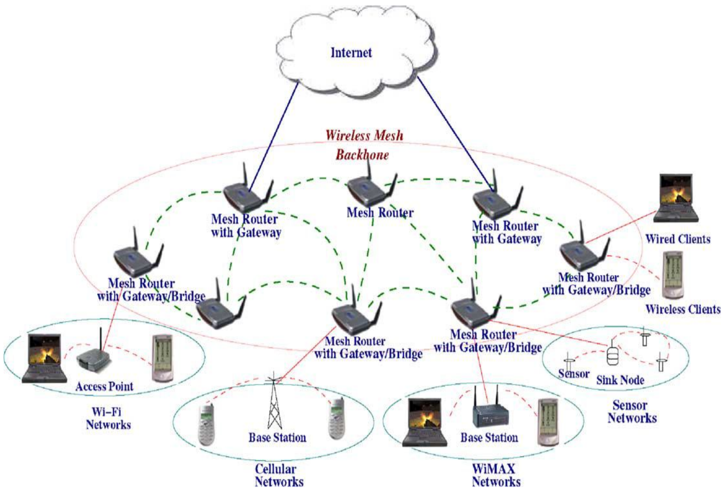

Figure 1 - Infrastructure / Backbone WMNs [1]

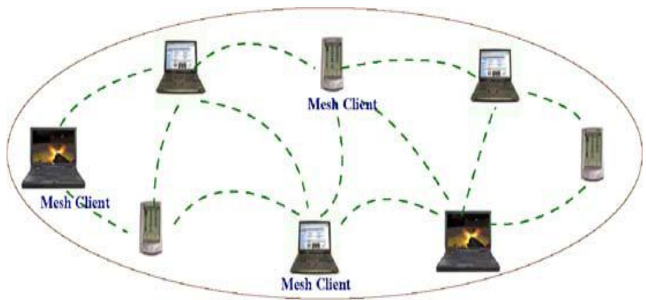

Figure 2 - Client WMNs [1]

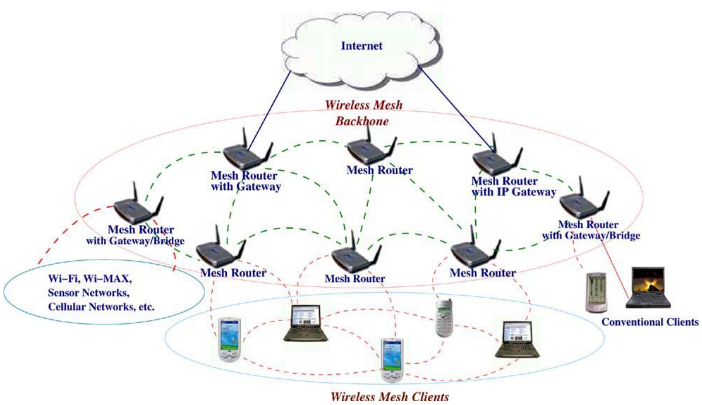

Figure 3 - Hybrid WMNs. [1]

3. CHARACTERISTICS AND CRITICAL ISSUES WITH WIRELESS MESH NETWORKS

Some of the important *characteristics* of the WMNs are

- Multi-hop wireless network,
- Support for ad hoc networking, capability for self-forming, self-healing, and self-organization,
- Mobility dependence on different type of mesh nodes (high mobility of MCs compared to MRs),
- Multiple types of network access (heterogeneity),
- Dependence of power-consumption constraints on different type of mesh nodes (MCs are relatively power constrained than MRs),
- Compatibility and interoperability with existing wireless networks,
- Dedicated routing and configuration,
- Mobility

Some of the *critical issues* influencing the WMN's performance are:

- Radio techniques (DSSS, FHSS, OFDM, QAM…)
- Scalability (throughput, bandwidth, coverage area…)
- Mesh Connectivity (neighbor list creation, deletion, modification),
- Broadband and QoS, (support for audio, video, image, combination of these)
- Compatibility and inter-operability, (integration with GSM, GPRS, 3G, 4G, WiMAX….)
- Security,
- Ease of use

All of these issues are equally important in order to consider WMN as a viable network for different class of applications and also for the replacement of wired internet. It is expected that WMNs will be setup with minimal number of routers to start with, in order to meet the current users' demands / requirements. As and when user population increases/decreases, the networks shall be enhanced with minimal deployment time and minimal number of MRs, without any degradation in service. Simply adding more MRs would not suffice, because the interference increase when more number of MRs are deployed within a specific area. On the other side, the connection drop rate / throughput go down if very few MRs are deployed. Thus the protocol layers shall be designed in such a way that the addition or deletion of MRs from network should have no / minimal impact on the network performance. Thus scalability of the WMN with changed network parameters (increase in number of users, applications with different bandwidth requirements (audio, video, voice, image), and users' data rate requirements) is of utmost necessity in order to accept WMN as a default internet service provider network for wireless users. In simple terms, the ***scalability*** can be defined as *an ability of a system, network, or process to handle a growing amount of work in a capable manner or its ability to be enhanced to accommodate that growth.*

The scalability of WMN can be classified in terms of different variants viz., *throughput scalability*, *bandwidth scalability*, *QoS scalability*, *network scalability across multiple hops*, *cross-layering for scalability*. The scalability of WMN can also be classified in terms of scalability support by different OSI layer viz., scalable PHY layer protocol, scalable MAC protocol, scalable ROUTING protocol, scalable TRANSPORT protocol and combination of these protocols with cross-layering technique. This paper discusses the existing literature on different ways in which the scalability of the WMN can be enhanced at the MAC layer applicable to WMNs.

Multihop communication is very common in WMNs. For multihop networking, it is well known that communication protocols suffer from scalability issues [15][16], i.e., when the size of network (number of users) increases, the network performance degrades significantly. Routing protocols may not be able to find a reliable routing path, transport protocols may lose connections, and MAC protocols may experience significant throughput reduction. The current IEEE 802.11 MAC protocol and its derivatives cannot achieve a reasonable throughput when the number of hops (between pair of MCs / between MC and MR) increases to four or higher [13] (for 802.11b, the TCP throughput is lower than 1.0 Mbps). The reason for low scalability of WMN is that the end-to-end throughput sharply drops as the network size increases. Due to ad hoc nature of WMNs, the centralized multiple access schemes such as TDMA and CDMA are difficult to implement due to their dependency on timing synchronization for TDMA (and code management for CDMA). When a distributed multihop network is considered, accurate timing synchronization within the global network is difficult to achieve [15]. Thus the distributed multiple access schemes such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is more favorable. However, CSMA/CA has very low frequency spatial-reuse efficiency [17], which significantly limits the scalability of CSMA/CA based multihop networks. To improve the scalability of WMNs, hybrid multiple access schemes with combination of CSMA/CA and TDMA or CDMA can be considered. In the following sections the existing literature related to scalability issues with WMNs are discussed in detail.

4. RELATED WORK

Majority of the existing literature discusses about enhancing performance of adhoc networks but those protocols cannot be used as is for WMNs because of the change in node mobility pattern in adhoc wireless networks when compared to WMNs. Adhoc wireless networks are widely utilized for data sharing amongst the set of users with one or more hops, whereas the WMN users intend to interact with public internet while servers could be located in wired / wireless networks. Hence WMNs are expected to support its services over multiple hops from client to server (multi-hop support). This is where WMNs differs greatly from adhoc networks and hence adhoc network protocols cannot be used as is with WMNs or adhoc network protocols shall be enhanced to work over multiple hops. The traffic flows are pointed towards servers (root nodes) in public internet and originated from WMN clients (leaf nodes), whereas the traffic flows in adhoc network are of peer-to-peer in nature.

Adhoc wireless networks expect the users to move very frequently, whereas the WMN users are expected to move slowly. Hence adhoc network protocols shall be modified / altered to consider minimal user mobility of users but are support the functionality over multiple hops. It is also observed that the MRs have zero mobility while MCs are expected move frequently. Hence we can safely assume the MRs can be AC powered while MCs are battery powered. Hence it may be a good idea to come up with different set constraint for MCs and MRs, thus adhoc network protocols are not directly usable for the WMNs. The existing literature on WMN scalability has been elaborated in the following sections:

A.Throughput scalability

A network is said to be throughput scalable, when the current set of users can obtain higher throughput with same infrastructure (number of MRs, MCs, and GWs), while the OSI layers of each these nodes are enhanced to reduce the interference / reduce access delay, reduce signaling overhead for the communication or any other changes to increase the throughput. The throughput can be enhanced in many ways, namely adaptive backoff mechanisms, transmission scheduling instead of contention based medium access. In either of these cases either idle time is reduced / collision probabilities are reduced to improve the throughput of the system.

Ghazale Hosseinabadi, *et al.* [3] observed IEEE 802.11 DCF (the MAC protocol currently used in WLANs), performs poorly when it comes to system throughput, channel utilization, and channel access time due to high system idle time or collision times. This paper proposed a distributed and dynamically adaptive MAC protocol for wireless networks, which focused on reducing system idle time and collision times by introducing an implicit token passing algorithm. According to this paper, a transmitting station schedules / selects one of its neighboring stations for the next transmission based on a distributed opportunistic algorithm. The *packet overhearing* is employed to populate the neighbor list and also to exchange the *scheduling* information across the network.

Peng Wang *et al.* [4] observed, Interference and Collisions greatly limit the throughput of mesh networks that use contention-based MAC protocols such as IEEE 802.11 DCF. Significantly higher throughput is achievable if transmissions are scheduled. However, the traditional methods to compute optimal schedules are computationally intractable (unless co-channel interference is neglected). If the co-channel interference is neglected and if it occurs, then the system performs poorly. This paper proposed a practical technique to compute optimal schedules based on an optimization problem, which searches for a low-dimensional optimization problem that has the same solution as the full problem. It is observed, such a low-dimensional problem is shown to always exist. The resulting algorithm converges geometrically fast or arithmetically fast, depending on whether the objective is to maximize the minimum throughput or to maximize the proportional fair throughput, where the minimum is over all the flows in the network. It is also found that proposed algorithms can compute optimal schedules within a few minutes for networks with 2048 nodes and within a few seconds for networks with 128 nodes.

Tehuang Liu *et al.* [5]proposed a novel idea to tackle multicast problem with the consideration of the interference between multicast trees in multi-radio multi-channel wireless mesh networks (MR-MC WMNs). The network is considered to using dynamic traffic model, i.e., request for multicast sessions arrive dynamically without any prior knowledge of future attempts. Each node in the network acts as a Transit Access Point (TAP), and has one or multiple radios tuned to non-overlapping channels. It is also proved that in MRMC WMNs, the minimum cost multicast tree (MCMT) problem that is, finding the multicast tree with minimum transmission cost, is NP-hard. The same problem is formulated by an Integer Linear Programming (ILP) model to solve it optimally, and propose a polynomial - time near - optimal algorithm, called Wireless Closest Terminal Branching (WCTB).

Ashutosh Deepak Gore *et al.* [6] observed that for a WMN to provide high throughput, the design of an efficient link scheduling algorithm is of paramount importance. They proposed three of link scheduling algorithms based on Spatial TDMA networks namely (a) Communication graph model of the network, (b) Signal to Interference and Noise Ratio (SINR) graph model of the network, (c) Communication graph model and SINR threshold conditions at receivers.

Kyu-Han Kim *et al.* [7]observed multihop WMNs experience frequent link failures caused by interference, dynamic obstacles, and applications' time varying bandwidth requirements. These failures cause severe performance degradation in WMNs or require expensive manual network management for their real-time recovery. This paper presents an Autonomous network Reconfiguration System (ARS) that enables a multi-radio WMN to autonomously recover from local link failures to preserve network performance. By using channel and radio diversities in WMNs, ARS generates necessary changes in local radio and channel assignments in order to recover from failures. Next, based on the thus-generated configuration changes, the system cooperatively reconfigures network settings among local mesh routers.

Erwu Liu *et al.* [8]addressed utility-based resource allocation in backbone WMNs. Unlike single hop cellular networks, a WMN shall support multi-hop transmissions with multiple contending links, and thus resource allocation shall be carefully designed to achieve the best results. The clique [1] based method with efficient spatial reuse is incorporated into Proportionally Fair Scheduling (PFS) for fair resource management in WMNs. They proposed a new algorithm named as clique-based proportionally fair scheduling (CBPFS) algorithm.

Guido R Hiertz et al. [9]proposed an extension to WLAN in order to provide network service to wireless users over multiple hops. WLANs were meant for providing last mile wireless internet access for the wired networks. WLAN forms the last hop of the wired backhaul and the latter is required to interconnect the Access Points (AP) which bridges the wired and wireless networks. The APs allow only for single-hop communication over wireless medium (WM). In order to bring wireless network access to un-served areas needed the setting up of wired backhaul. IEEE 802.11s fills this gap of extending wireless connectivity over multiple hops and reduces the effort in setting up and configuration of the wired backhaul. With 802.11s the infrastructure dependency of WLAN has been removed and self-contained WMNs of arbitrary topology can be formed. The 802.11s based WMN may also serve as a transparent backhaul for other networks as well. This work also proposed a new MAC protocol based on distributed reservations that allow for scheduled access to the wireless medium.

R. C. Carrano *et al.* [10]presented a tutorial on 802.11s based multi hop MAC protocol for wireless mesh networks. The proposed mesh network is implemented at the link layer, relying on MAC addresses rather than IP addresses for its mechanisms. This feature enables the design and development of new CPU-free network devices that provide layer-2 multihop communication. The existing WMN implementations are based on the layer-3 forwarding, because these networks are based upon 802.3 (Ethernet) or 802.11 (WLAN), 802.16 (WPAN) which are based on layer-3 forwarding. If the data link layer can forward the packets for the wireless mesh routers, then it would considerably reduces the processing time for the mesh router. Thus the transmission delays across multi hop networks can considerably be reduced because of layer-2 forwarding.

B. Cross-layering for scalability

Yuefeng Huang *et al.* [11]proposed a Cross-Layer approach for mesh access networks to simultaneously address the challenges namely, unidirectional link problem, heterogeneous hidden problem, heterogeneous exposed problem, and improve network performance. The main idea of the proposal was to eliminate the unidirectional link at the network layer and design a novel hand-shake and channel reservation mechanisms at MAC layer using topological information collected in the network layer.

C. Bandwidth scalability

Jian Tang *et al.* [12]discussed end-to-end bandwidth allocation problems in cognitive radio WMNs with the objective of achieving a good trade-off between fairness and throughput. They have defined two fair bandwidth-allocation problems, namely, (a) the Max–Min fair Maximum throughput Bandwidth Allocation (MMBA) problem and (b) the Lexicographical Max–Min (LMM) fair

[1] Clique – An exclusive circle of people with common purpose.

Bandwidth Allocation (LMMBA) problem. It is also proposed that Linear Programming (LP)-based optimal and fast heuristic algorithms for both problems (MMBA & LMMBA). It has been shown by numerical results that the throughput given by the MMBA and LMMBA algorithms are very close to the corresponding maximum achievable throughput. It is also observed that LMMBA algorithm achieves the fairest bandwidth allocation.

D. Network Coverage area scalability

Adel Aziz *et al.* [13]proposed a detailed discussion on the root causes for instability of CSMA-based wireless mesh networks, where a network is said to be stable if and only if the *queue* of each relay node remains (almost surely) finite. It is found that two factors which impact stability namely, the network size and stealing effect (A consequence of the hidden-node problem and nonzero transmission delays). Considering greedy sources, it was proved using Foster's theorem, that three-hop networks are stable, but only if the stealing effect is accounted for. It is also observed that four-hop networks are, on the contrary, always unstable (even without the stealing effect problem). To tackle the instability problem, distributed flow-control mechanism called EZ-flow was proposed, which is fully compatible with the IEEE 802.11 standard (i.e., it does not modify headers in packets). The paper also inferred that *the wireless mesh network works normally without any service degradation when number of hops between users are less than or equal to three hops but become unstable when it became more than THREE hops.*

5. CONCLUSIONS AND SCOPE FOR RESEARCH

From previous section, it is observed that the coverage of any WMN router limited to THREE hops, beyond which the throughput drops significantly and is not suitable for supporting required QoS to end users. Thus the upper limit on coverage area of any multihop network shall be set to be three hops from the specific MR. In order to support wireless internet service over a large area, it is necessary that a set of mesh routers shall be deployed in a specified area such that the a mesh topology of wireless routers is formed. The mesh routers shall be programmed in such a way that the channel allocation is coordinated amongst the set of routers within a specified geography. To distribute the set of mesh routers, cluster based algorithm [14]can be used. Thus optimal number of MRs can be deployed to serve a specific geography within which users were permitted move on. Hence the WMN coverage can be extended beyond THREE hop distance from a specific MR, without any wiring between mesh clients / routers.

From previous sections it is also inferred that a Mesh Router with scheduling based MAC protocol, multi-radio multi-channel (MR-MC) support and clustering of these MRs shall greatly scale the WMN for larger area, large number of users. Till date, there is no effort has gone into explore the feasibility of Mesh Routers with MR-MC support with 802.11s MAC. This can be considered as a potential open issue for further research.

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BIBLIOGRAPHY OF AUTHORS

Mr. Nataraju A.B. graduated in Electronics & Communication Engineering from Dr. Ambedkar Institute of Technology (Dr. AIT), Bangalore, INDIA in 1997. In 2001 he received his Master of Engineering degree from University Visvesvaraya College of Engineering (UVCE), Bangalore, INDIA. Currently he is pursuing Ph.D degree in Department of Electronics and Communication Engineering at Jain University, Bangalore, INDIA. He has got 15 years of total experience, which includes 9 years of industrial experience with major telecom companies namely Huawei Technologies, Wipro Technologies, Sonus Networks and Kodiak Networks. His research interests include Computer Networks, Wireless Networks, VoIP, and Signaling Protocols.

Dr. H.D. Maheshappa Graduated in Electronics & Communication Engineering from University of Mysore, India in 1983. He has a Post Graduation in Industrial Electronics from University of Mysore, India in 1987. He holds a Doctoral Degree in Engineering from Indian Institute of Science, Bangalore, India, since 2001. He is specialized in Electrical contacts, Micro contacts, Signal integrity interconnects etc. His special interests in research are Bandwidth Utilization in Computer Networks, Wireless Networks. He has been teaching engineering for UG & PG courses for last 28 years. He served various engineering colleges as a teacher, professor and at present he is the Principal and Professor of Department of Electronics & Communication Engineering in Acharya Institute of Technology, Bangalore, India. He has more than 50 research papers in various National and International Journals & Conferences. He is a member of IEEE, ISTE, CSI & ISOI. He is a member of Doctoral Committee of Coventry University UK. He has been a Reviewer of many Text Books for the publishers McGraw-Hill Education (India) Pvt. Ltd, Chaired Technical Sessions, National Conferences and also has served on the advisory and technical national conferences.