Topological-based Architectures for Wireless Mesh Network

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Abstract

The Wireless Mesh Network (WMN) and the associated IEEE 802.11s standard have attracted an enormous amount of research in the wireless research community for the past few years. Nevertheless, WMN architecture has not received much needed attention compared to other topics in this area of research. Based on topological differences, various network architectures are possible for WMN, and we believe such architectures could affect wireless characteristics differently. In this article, we provide an overview of architectural design approaches for WMN, then summarize the state-of-the-art research findings and suggest further topics that need to be addressed. Additionally, we identify three different types of architectures for WMN: Campus Mesh (CM), Downtown Mesh (DTM), and Long Haul Mesh (LHM). Furthermore, we discuss and investigate different WMN characteristics that could be affected by commonly deployed architectures. Among the considered characteristics we select routing, network management, and network performance for further analysis, and look at the challenges that these architectures are facing with respect to those characteristics. To illustrate these challenges, we perform a simple experiment to show that LHM and DTM under identical network environment show significant differences in performance parameters such as throughput and delay.

Keywords: Wireless mesh network architecture, topology, routing, network management and performance.

1 Introduction

Wireless Mesh Networks (WMNs) have been the subject of much discussion in recent years for the promising improvements they bring to many problems of ad-hoc networks, as well as their practicality and effectiveness in many areas of difficult terrain. A vast amount of research has been performed in different areas of WMN, such as network performance, routing, applications, etc. However, most research works do not identify the type of architecture design they work in, and fail to address whether their solutions could generate the same results when implemented for different types of WMN architectures.

WMN architecture could take different topologies based on structural design and orientation of its components with respect to each other and to the network environment. Such variations in the architecture of WMNs could pose fundamental differences in the physical characteristics and performance of the network, which in turn could yield different results in the performed studies. Such differences necessitate architecture-dependent solutions for each problem. Thus an in-depth study of different types of architectures is important and critical for WMNs, which could potentially elucidate some of the challenges facing WMN in research areas such as applications, routing, network management, and network performance.

In this article, we identify three main stream architectures for WMNs, namely Campus Mesh (CM), Downtown Mesh (DTM), and Long Haul Mesh (LHM), and explain their fundamental differences as well as some important factors that could be affected by the type of architecture. We then discuss how the dynamics of routing, network management, and performance of WMNs could be affected by the characteristics of the architecture, without getting into detailed analysis or evaluation of those factors.

The remainder of this article is organized as follows. In Section 2, we give a brief literature review. In Section 3, we identify three distinct types of topological architectures. In Section 4, we outline major network characteristics which could be affected by the type of the deployed architecture, and we show performance variations using system throughput for different architectures. Finally, we conclude our findings and make recommendations to be considered in WMN research studies in Section 5.

2 Related Works

The IEEE 802.11s is associated with WMNs, which defines the interoperability between WMNs and Wireless Ad-Hoc Networks. The IEEE 802.11s MAC layer defines architecture for WMN including protocols to support broadcast, multicast and unicast connections for a self-configuring multi-hop network combining backbone of fixed Wireless Mesh router (WMRs) and clusters of Mobile Nodes (MNs) [15].

To the best of our knowledge, few research papers exist in the literature; clearly addressing the importance of the architecture of WMNs. Akyldiz et al [2] identify, for the first time, three distinct architectures for WMN. They classify three architectures as Infrastructure/Backbone, Client, and Hybrid WMNs. Their classification is based on the functionality of WMRs versus MNs. Nodes in the Backbone architecture have different functionality than those in the Client architecture. In the Infrastructure WMNs, the authors introduce WMRs in the backbone, connecting to MNs and collecting traffic from them. Then WMRs forward the traffic to the Internet backbone via access points. In the Client WMNs the authors introduce peer-to-peer connectivity of MNs, and totally remove the need for WMRs. The Hybrid WMN is basically a combination of the other two architectures.

Waharte and Boutaba proposed a tree-based architecture for WMNs [3]. They identify two types of WMRs, namely Access Point (AP) and Network Gateways (NG). In their tree-based architecture, APs collect traffic from MNs and pass it to NGs in a two-layer hierarchical fashion, where MNs connect to the Internet through NGs rather than exchanging peer-to-peer traffic. Therefore, traffic streams will mainly be directed towards/from the NGs, causing a bottleneck in the access network. Based on these findings, the authors conclude that a tree-based or hierarchical architecture would suite WMNs most perfectly.

sMesh (or seamless Mesh) architecture is introduced in [4]. The authors propose an architecture which is entirely based on the backbone and WMRs. It is also totally transparent to MNs. That means the entire WMN is seen as a single AP from the point of view of MNs. They add a connectivity monitoring system to the functionality of WMRs that constantly monitors connectivity power for each MN, and finds the strongest connected AP to which the MN will communicate. In this architecture, a higher density of WMRs in the backbone ensures that all MNs have always good connections to the WMN.

Recently, BelAir Networks has taken a new approach in categorizing different architectures of WMN [11]. The authors distinguish different structures based on the number of radios used on WMN nodes. They identify three types of architectures: single-radio, dual-radio, and multi-radio mesh networks. Each structure includes a string of APs connecting several clusters of MNs. In this type of WMN categorization, a single radio wireless mesh has low capacity and does not effectively scale to implement a complete network solution, whereas a dual-radio mesh architecture could scale to a metro dimension, since using different radios, it separates traffic and reduces interference to improve the capacity. On the other hand, a multi-radio mesh system separates wireless access and backbone by using a dedicated point-to-point link to form a wireless backbone. This provides for a high capacity system that can support large networks with a wireless broadband service for the end user.

WMNs can be implemented using different types of wireless technologies such as Wireless Local Area Network (WLAN) or Worldwide Interoperability for Microwave Access (WiMAX), or using cellular technologies such as Universal Mobile Telecommunications System (UMTS) or Long Term Evolution (LTE). In recent years, WiMAX networks and new generation of cellular networks such as LTE have been proposed as the backhaul for the WLAN to build a new generation of WMNs which integrates various wireless technologies to fulfill one of the promises made by 4th Generation (4G) wireless technologies [13-14].

Several wireless technology leaders and service providers including StrixSystems [16] and Tropos Networks [17] have recently introduced a WMN architecture called MetroMesh, which covers areas at metropolitan scale. However, they have not addressed other possible architectures to include smaller environment such as Campus or larger environments such as Longhaul, and stop short of characterizing WMNs based on different architectures.

3 Description of the WMN Architectures

WMN is a self-configured, self-organizing, multi-path and multi-hop network which consists of fixed WMRs in the backbone and MNs in the access network. In this section, we first introduce the general or baseline architecture for WMN including all equipment, interfaces, links, and protocols. Then we describe how this architecture is implemented in three completely different operating environments, namely Campus, Downtown, and Long Haul Mesh. All architectures follow the general structure outlined in the baseline. However, they differ on how their backbone and access networks are topologically designed and connected to each other. These architectures could be combined in order to build more complex hybrid structures, and could be customized to fulfill specific requirements set by clients.

3.1 Wireless Mesh Network Baseline Architecture

WMN baseline architecture is based on the connectivity and physical orientation of different types of WMN nodes. There are essentially two types of nodes: WMRs and MNs as illustrated in Figure 1. WMR can be classified as three types: Backbone Mesh Router (BMR), Access Mesh Router (AMR), and Internet Access Point (IAP) depending on which part of the mesh network they are located in. Each MN is connected through an access link to an AMR, which serves as a gateway to the backbone network. The BMR is in the core of the mesh network and does not have access functionality, nor does it have any MNs connecting to it. IAPs serve as gateways to the Internet for the entire WMN. All WMRs have gateway/bridging functionality, which is not required for the MNs.

Although other technologies such as WiMAX and UMTS have been proposed for the backbone of WMN, in this study all assumptions are primarily on WMN based on the IEEE 802.11 WLAN with a/b/g/s amendments. The backbone interfaces are equipped with the 802.11a (in the infrastructure mode of operation), access interfaces with the 802.11b/g (in the ad-hoc mode of operation), and the mesh definitions are based on the 802.11s. A general overview of WMNs is presented in Figure 1.

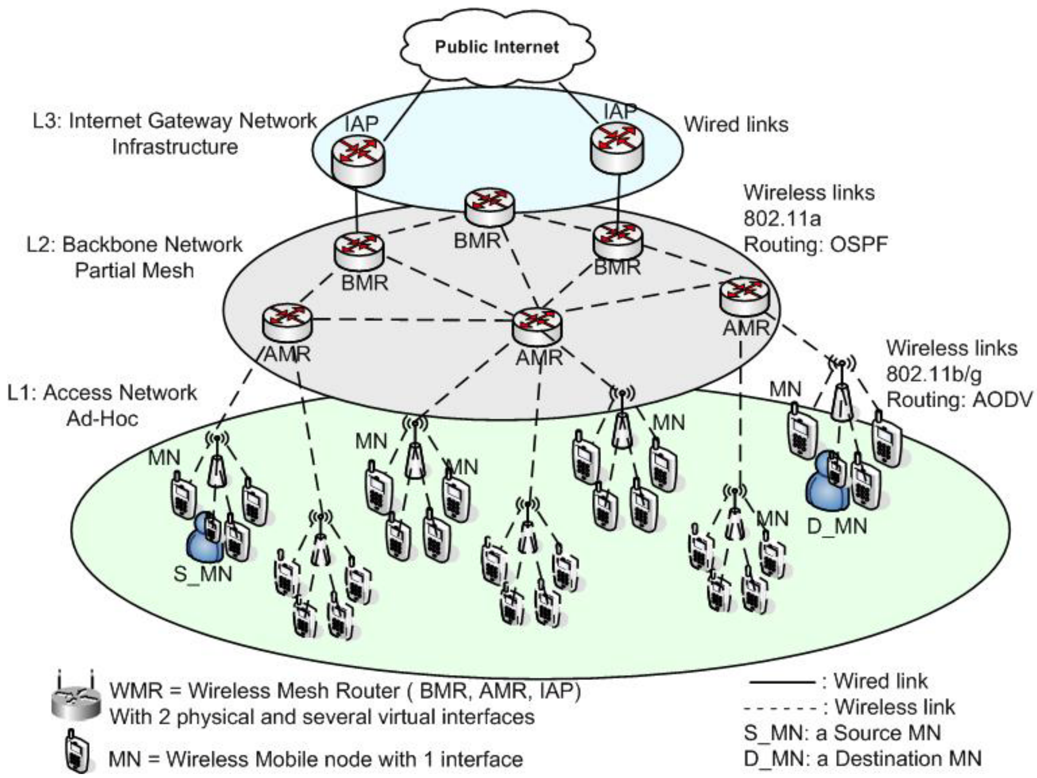

Figure 1: Wireless mesh network baseline architecture.

Generally, a WMN has two distinct parts: a backbone network and an access network. The backbone network is a collection of various types of WMRs connected to each other. The access network, on the other hand, is a collection of several clusters of MNs. Each AMR acts as a cluster-head for its corresponding cluster of MNs, collects traffic from MNs and forwards it to other AMRs or BMRs for uplink delivery to the Internet via IAPs. Backbone is a group of different types of WMRs organized in circular, ad-hoc or longitudinal fashion depending on whether the architecture is CM, DTM, or LHM respectively. The WMRs are often fixed, stable and have access to unlimited power supply. They use proactive routing protocols such as the Open Shortest Path First (OSPF) protocol. Access is a group of clusters, each containing several MNs. These clusters are highly mobile and unstable, use temporary source of power, and use on-demand and ad-hoc routing protocols such as Ad-hoc On-demand Distance Vector (AODV).

All the links in the backbone and access networks are wireless, established using 802.11a and 802.11b/g respectively. AMRs are equipped with two physical interfaces; one to connect other WMRs in the backbone, and the other to connect to MNs in the access network. All WMRs in the backbone use multiple virtual interfaces to connect to multiple peer WMRs to build a partial mesh as depicted in Figure1. MNs use 802.11b/g contention MAC to access shared channels and connect to their clusterhead AMR.

The baseline details mentioned here are shared by the three identified architectures in the next section. The difference is in the topology; the geographical location and physical orientation of the equipments with respect to one another and to the network environment. In the next section we identify the fundamental differences among each type of the architecture.

3.2 Campus Mesh Architecture

In the CM architecture (Figure 2), a limited number of buildings are located in a campus environment, with generally good Line of Site (LOS), and central management and administration unit. WMRs could simply be installed on existing infrastructure in campus. The number of MNs in such environments is usually fixed and MNs have little or no mobility, since the wireless equipments in a campus environment have little or no movement once they are stationed in a location. The entire network is usually under a single administration and is controlled by a single Internet Service Provider (ISP). Traffic could be easily monitored, and the amount of exchanged traffic could be easily predicted during different time periods, resulting in a more static and predictable network requirement. Thus, the network in CM architecture is generally easy to deploy, monitor, manage and upgrade.

These features provide a highly flexible environment for deployment of WMN. Due to single administration provisioning, it is easy to monitor and control different aspects of the network management, such as routing, congestion and interference control. CM is the most flexible environment of the three architectures. It is also the simplest architecture to be deployed.

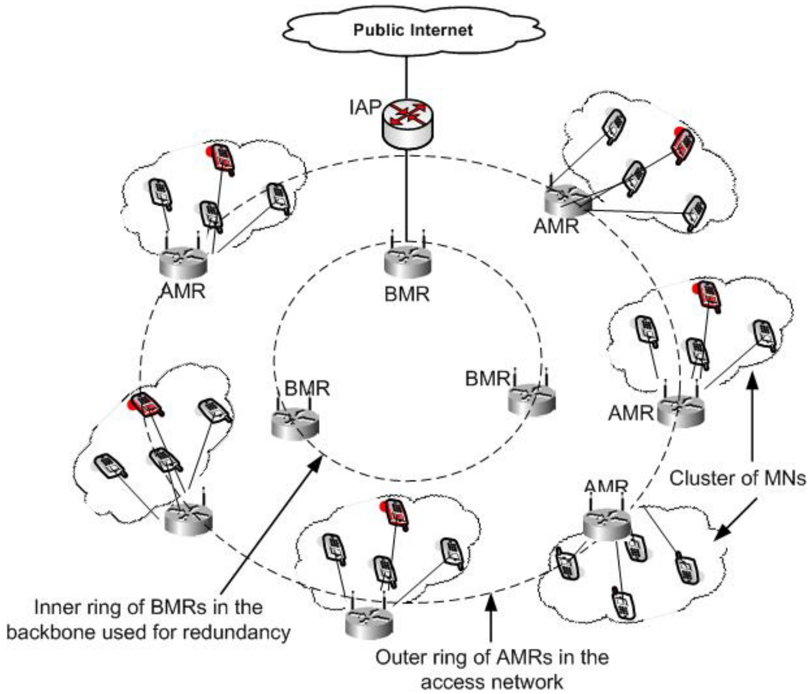

Figure 2: Campus mesh architecture.

Figure 2 shows a typical CM architecture, where there are two rings of WMRs in the backbone: inner and outer rings. The outer ring essentially represents AMRs connecting MNs to the backbone. The BMRs are in the inner ring, with no direct connection to the access network. Due to high concentration of MNs in CM, some of the inner ring BMRs could also act as an AMR. The inner ring has several major functions; to act as a redundant array of routers or a backup path in case of congestion or disconnection, to provide multi-path routing options to the AMRs, and to collect traffic and pass it to IAPs for internet connectivity.

3.3 Downtown Mesh Architecture

In the DTM architecture, many buildings ranging from small to large are scattered over several blocks in a downtown environment as shown in Figure 3. This type of architecture introduces many challenges in terms of deployment, management, and control. Generally, LOS is not adequate, and towers are not available or accessible in many locations. The number of MNs varies with time and MNs tend to change their locations frequently around the downtown area. The network could be under different administration and management, or even different ISPs, which introduces more technical and billing difficulties, such as roaming and network sharing among ISPs.

In terms of traffic load and prediction of traffic behavior, this type of architecture is quite different from CM. In CM, the majority of traffic is generated by the users on the campus, such as employees in an enterprise or students in an institution campus. The number of employees, the type of operation, application and usage are well known to the administration over time.

DTM, on the other hand is usually the harshest environment, where one does not know what to expect in terms of real time traffic. The number of users passing by, the type of traffic that they are using, the time and the day they are passing by, and other factors could very well change the fluctuations of the amount of traffic. Exchanged traffic is highly bursty depending on different client operations, different time of the day, week, month or even year. Different ISPs provide different types of services to their clients, which makes it extremely difficult for them to coordinate with one other. The complication in management and billing coordination could increase significantly.

DTM requires thus a more advanced, high capacity network and costly equipment for deployment. Coordination between ISPs is required and constant city involvement and licensing issues should be taken into consideration. Such technical and management difficulties could make the solution not as viable as originally thought.

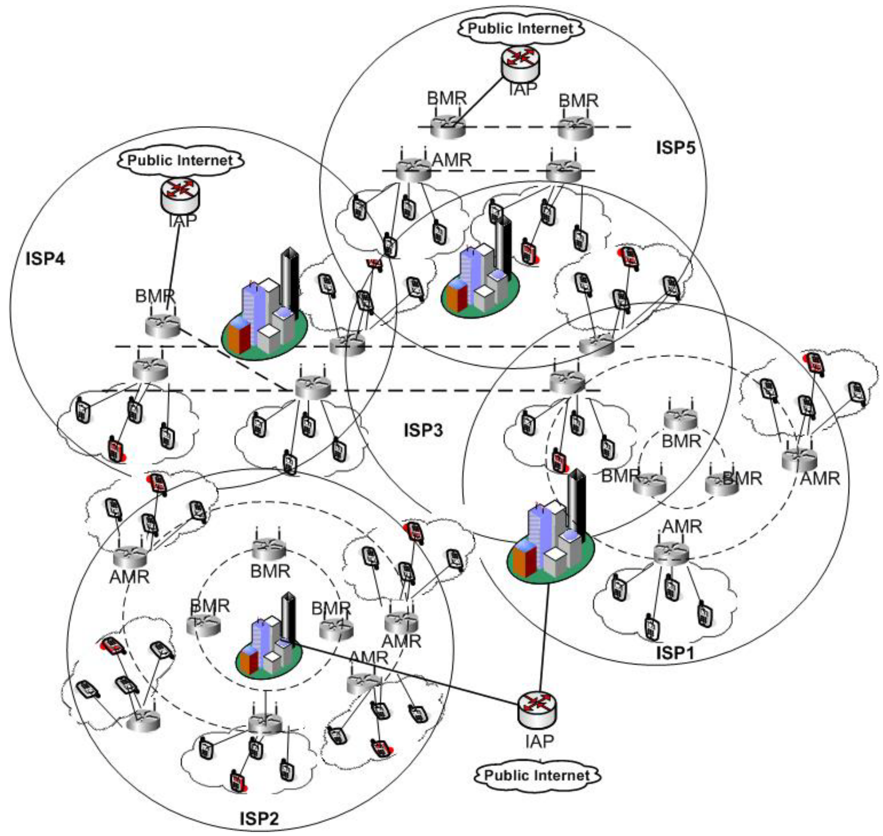

Figure 3: Downtown mesh architecture.

3.4 Long Haul Mesh Architecture

In the LHM, there are no buildings around, but rather a long set of WMRs along a stretch of a highway inside a city, or in the suburban areas, where there is no infrastructure in place or it is difficult and costly to deploy one. The WMRs could be apart as far as their transmission range allows. Lack of abstraction allows for long LOS using single powerful unidirectional antennas between each pair of adjacent routers. Deployment could prove simple, where antennas are positioned at great heights, kilometers away from each other, depending on their transmission power. A second set of routers (BMRs) could be deployed on the other side of the roadway for redundancy, as depicted in Figure 4.

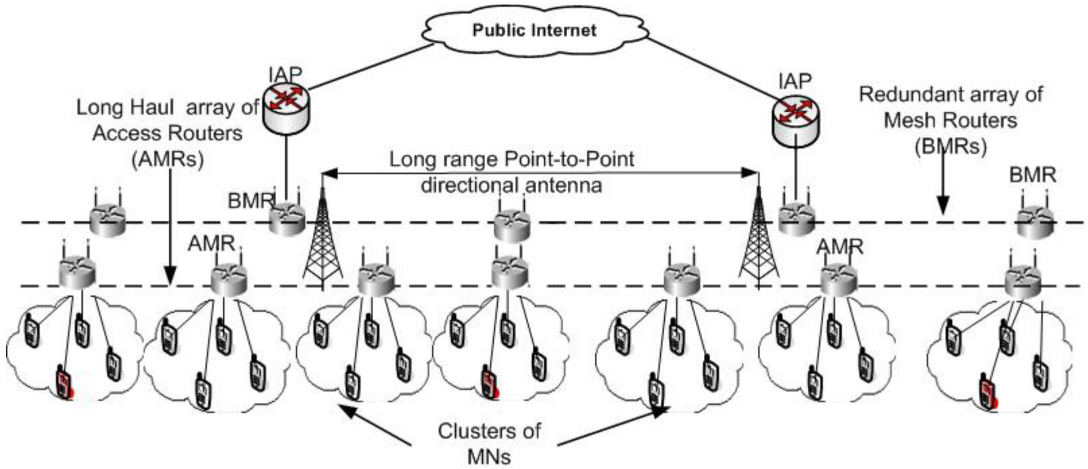

Figure 4: Long haul mesh architecture.

LHM is a phenomenal solution for networking and communications, because it eliminates the need for extensive and costly infrastructure, as required by traditional wired and wireless technologies. In [8], the authors propose LHM architecture for the first time, along with a routing scheme which involves OSPF and Border Gateway Protocol (BGP) routing protocols in the backbone and AODV with an alternative routing path through the access network.

It is generally agreed that multipath routing is a viable solution for WMN routing. On the contrary, with the multipath routing, there is not much gain for LHM architecture, since there are not many possible paths between a pair of source and destination nodes. The only backup solution is an array of redundant BMRs that runs along with the main backbone of AMRs.

3.5 Differences between CM, DTM, and LHM architectures

The three identified architectures are fundamentally different in terms of technical details as well as management. Each type of architecture possesses advantages and pitfalls. There are numerous studies that evaluate the performance of various WMNs in their respective environment and unique architecture [2]. Performance of each type of architecture is adjusted and optimized to its specific characteristics and environment. For instance, physical and MAC layer characteristics could be adjusted or links with different capacities could be used to improve performance of one type versus another. In this paper, however, the main objective is to highlight the differences and their consequences without getting into detail of performance analysis. In section 4.3, we create a simple case to highlight one of the areas that shows clear differences among architectures. Differences between CM and DTM fall into two major categories *i*) differences between the two in ISP management problems and *ii*) differences in network issues such as routing, congestion and interference due to cluster density of MNs. The major difference between LHM and the other two architectures consists in the structure itself, the type of equipment, and the lack of multipath routing in LHM. Table 1 summarizes the basic characteristics and differences of the three types of architecture.

Table1: Basic characteristics and differences of the identified three architectures.

Architecture	Area Km^2	Management	ISP	Line of Site	Users
Campus	1	Enterprise	Single	Well	100's
Downtown	10	City	Single/Multiple	Inadequate	1000's
Long Haul	1000	State	Multiple ISP	Excellent	Unlimited

4 Pretentious Network Characteristics

In this section we present some factors or network characteristics that could be seriously affected and severely constrained by the implemented architecture in WMNs. We explain the most important factors that have direct effect on the WMN when a particular architecture is used. However a long list of such factors can be pointed out based on applications and solutions proposed for different areas of WMNs.

4.1 Routing in WMN

Several routing protocols are proposed for WMN such as AODV, DSR (Dynamic Source Routing), and OSPF. OSPF is proposed and deployed in the backbone by many research groups and vendors, such as Nortel Networks. However a difficulty with implementing OSPF in the backbone consists in the fact that OSPF works in a hierarchical fashion. This structure includes a backbone area (i.e. *area0*) in the root and several other areas all connected through *area0*.

Hierarchical OSPF areas would nicely fit into the DTM architecture where the main buildings are surrounded by smaller offices, and to a lesser extent for the CM architecture. However, in the LHM architecture, it would be impractical to deploy OSPF in a hierarchical fashion. This is due to the fact that traffic from all other areas need to go through the *area0* before reaching its destination. This causes an enormous amount of traffic to pass through *area0*, which results in an *area0* bottleneck.

A multipath routing in the backbone is introduced to improve the quality and the performance of WMN routing. Several multipath routing protocols have been proposed for WMN [5] along with their extensions as well as new metrics for performance measurement [6]. Multipath routing could be applied in DTM or CM architectures. However, in a LHM architecture where the WMRs are stretched longitudinally along hundreds of kilometers of highways, LHM could not gain much by using multipath routing.

4.2 Network Management

One of the issues facing WMN consists in network management and network ownership by multiple ISPs. As the size of a network increases, more than a single ISP could get involved in managing the entire network [2, 7, and 9]. Traditionally each Wireless LAN is managed by a single ISP. However for larger networks that could range over hundreds of kilometers, or hundreds of buildings in a downtown area, different parts of the network most likely fall into territories of different ISPs, and could pose complications in management such as roaming, billing and handoff between different networks. Although ISP management could introduce serious issues in case of LHM and DTM architectures, it does not pose any problem in case of CM architecture. In a CM architecture where most of the network management is handled by a single ISP or even occasionally handled locally by in-house network administration, there will be no need for ISP or management coordination and consideration. Therefore, individual solutions could be developed for CM problems that do not concern management issues similar to those of DTM or LHM.

Using multiple ISPs in large networks has also been proposed for load-balancing as well as for other network management issues. In wired networks, BGP is the protocol of choice for network management and employment of multiple ISP solutions. WMN architectures such as LHM and DTM could also use BGP in the backbone, and provide a viable solution and replacement for the last-mile networks.

4.3 Network Performance

Network performance for WMNs has been the subject of much debate in the wireless research community in the past few years. Many studies have introduced new and improved solutions throughout various TCP/IP layers to optimize network performance for WMN [2]. Some have suggested performance improvements through new metrics in a cross-layer fashion that could incorporate link qualities in routing [6]. Most of these solutions propose different schemes by which WMN performance could be improved.

Others studied performance issues that come from interference. Usually MNs in a cluster engage in communication with AMRs and with other MNs causing multiple levels of interference. Interference could be a major obstacle in a DTM network where backbone routers are closer to each other and ad-hoc MNs are moving. On the other hand, when LHM architecture is deployed in a suburban area, there are only few WMRs, and they are deployed far apart. In this kind of structure, interference is minimal and does not affect the functionality of other nodes and routers.

An increasing number of MNs in a cluster will decrease the throughput and, consequently, degrade the performance of WMN. In [8], the authors show that the performance degradation is caused by contention among MNs accessing the wireless channels while trying to establish communication with AMR. Several solutions have been proposed for the contention problem such as using multi-channel and multi-path schemes in signal propagation and routing solutions.

In this section, we evaluate and compare the performance of various architectures. We only perform throughput measurements to highlight differences among the different architectures. One can find more detailed performance analysis for WMNs in the literature [2, 8, and 12]. Our throughput hypothesis states that i) performance degradation is due to reduction in throughput caused by contention among MNs for medium access on the link to AMR, and ii) such a performance measure is highly affected by the orientation of the AMRs and MNs, and the type of architecture in the WMNs. Therefore, it is expected that throughput results for different architectures show significant differences.

A simulation model and experiments are implemented and carried out in the OPNET modeler 14.5 PL1. We implemented CM, LHM and DTM architectures with the same network environment such as equipments, applications, and traffic. In each model, there are twelve routers and six clusters with two MNs in each network. OPNET has different options for generating traffic at various layers with unique specifications, such as Mobile Ad-hoc Network (MANET) traffic. MANET traffic is generated between a source (S_MN) and its contending MNs, and a destination (D_MN) with specifications as in Table 2. The throughput statistics are collected for each scenario. MNs use TDMA for medium access, and all WMRs are using the AODV routing protocol. The experiments are repeated five times with seed number multiplied 20 times, which makes the results averaged over 100 times.

Table 2: Traffic parameters generated from S_MN to D_MN.

Traffic Parameter	Value
Start time	100 sec for S_MN and 0 sec for contending MNs
Poisson arrival	Inter-arrival time = 0.01 Sec
Rate (Packet size)	8192 and 16384 Bits/Sec, (for contending MNs and S_MN respectively)
Destination	AMR and D_MN, (for contending MNs and S_MN respectively)
Stop time	300 Seconds

In each simulation experiment we gradually increase the number of MNs in the source cluster from two to six and monitor the changes in the system throughput values. Figure 5A shows the changes in throughput for LHM architecture. As the number of MNs increases from two to four, there is a twofold increase in the system throughput. However by further increasing MNs to six, the contention problem causes the throughput to decrease to just above that of two MNs.

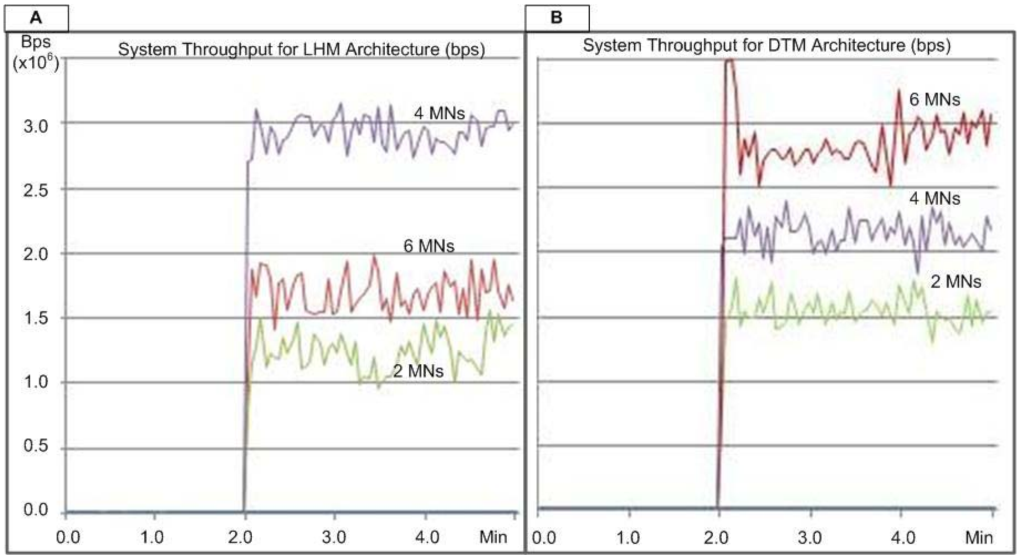

Figure 5: Overall system throughput for LHM (A) and DTM (B) Architectures.

Figure 5B shows corresponding results for DTM architecture. These results are significantly different from those of LHM. As we increase the number of MNs from two to four, the throughput increases by 25%. As we increase the number of MNs to six, the throughput increases at a steady rate by another 25%. This shows that the contention is not affecting the network performance as severely as in the LHM architecture. This linear performance changes can be attributable to several reasons. Intuitively, in a dense DTM environment when a MN has many contending neighbors, it seeks other paths to reach the destination, thereby increasing the system throughput at a more linear way than the LHM Architecture.

The link throughput for the link between AMR and D_MN at the destination (results in Figure 6) could illustrate the contention factor more clearly. Figure 6A shows that in case of LHM architecture, the link throughput at destination does not change significantly as we increase the number of MNs from two to four. However, as we increase the number of MNs in the cluster to six, the contention factor is more obvious: the link throughput drops from over 100 kbps to around 70kbps in case of two MNs. In case of DTM, however, the results are quite different. The link throughput is decreasing at a steady rate. This is due to the fact that in DTM, by increasing the amount of traffic, interference and congestion could decrease the link throughput at a constant rate by around 5-10% drop for every two MNs added to the source cluster.

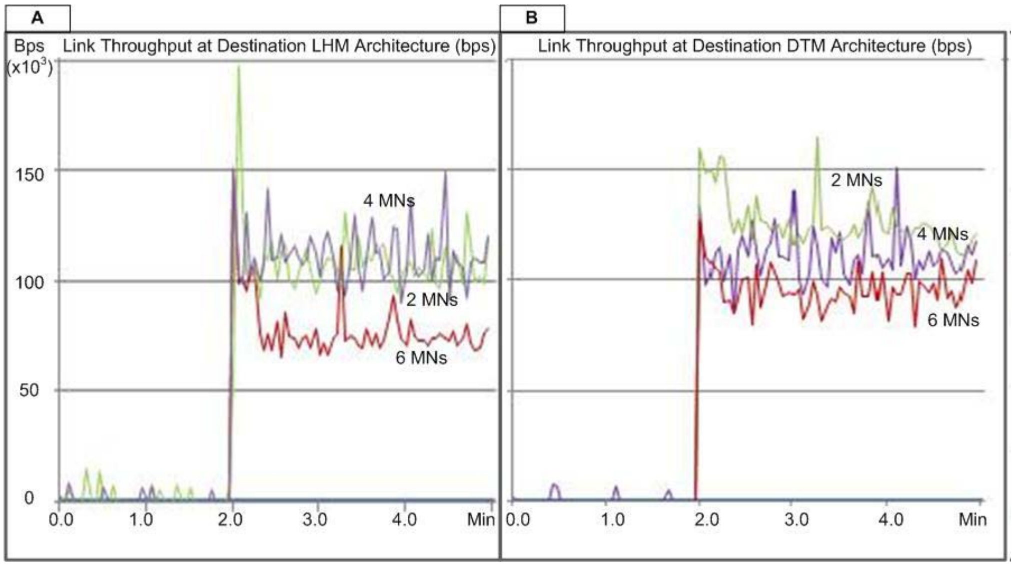

Figure 6: Link throughput at destination for LHM (A) and DTM (B) Architectures.

In terms of delay analysis, as illustrated in Figure 7, in both cases, the delay is the least for the scenario with two MNs. As we move to 4 MNs, the delay increases for DTM at a slow rate by less than

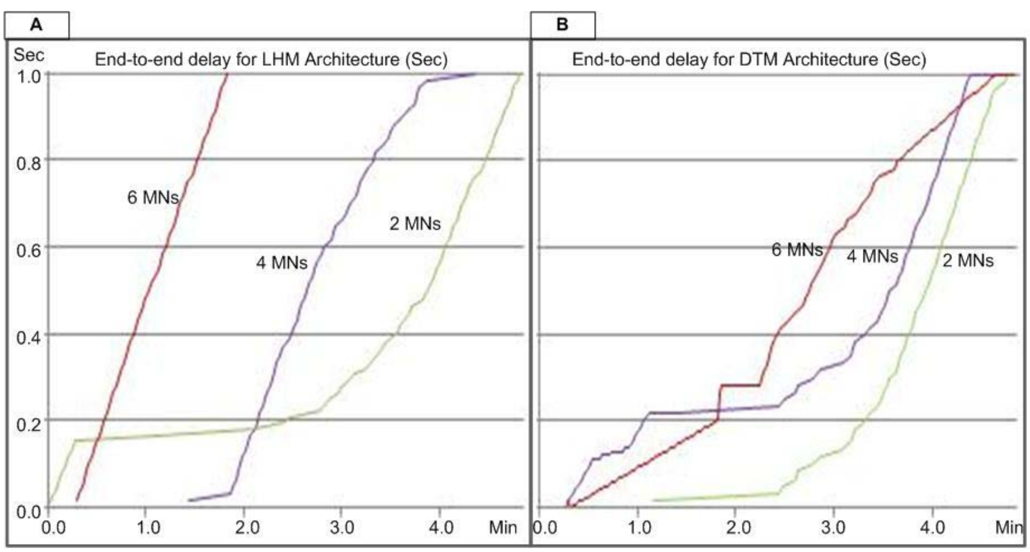

Figure 7: End-to-end delay results for LHM and DTM Architectures

5% for 4MNs and less than 8% for 6 MNs. However, in case of LHM, the delay follows a slightly higher increase to over 10%. However, as we move to 6 MNs, the delay increases dramatically to over 70% compared to the case of two MNs.

These results show that there is no proportional relation between the number of MNs and system throughput in LHM compared to DTM. Clearly contention exists in both cases. However, its effect becomes insignificant when other architectural features as well as other constraints are included in the equation.

In this article, we are not trying to generalize the results or declare which type of architecture is the best. We merely highlight the impact of these architectures on the performance. Regardless of the reasons, these results clearly support our hypothesis that different types of architectures generate significantly different results in performance analysis and measurements. Further they show that differences are so significant that proof of a point in one type of architecture could not support the same point in another type of architecture.

5 Conclusion and Recommendations

Recent research on WMN has not adequately addressed various architectures of WMN. WMN could assume different types of network architectures, and the type of architecture could affect wireless characteristics differently. In this paper, we identified three types of architectures and various network characteristics that could be differently affected by each type. We pointed out three major areas, in which the differences are highlighted among the three architectures, and showed by simulations that performance measures such as throughput and delay could vary significantly depending on the underlying architecture. We recommend that WMN architecture should be considered as an integral part of research activity and those experiments in this area clearly distinguish and identify the scope of the network as well as its type of architecture. Various solutions in different areas of WMN have been proposed in recent years, and experiments have been developed to prove or disprove proposals based on single architecture types. We further recommend investigating the validity of such proposals under various types of architectures.

In the future, we plan to propose standard structural definitions for the identified architectures and for other hybrid architectures that could be built based on the three main stream architectures mentioned in this paper. We will also identify a complete list of factors at different layers, such as application, network and MAC layers that could be affected by the architecture type. We would further like to investigate the accuracy of several proposed solutions based on different architectures, and investigate their reliability to see if they apply to all kinds of architectures, or only to one type.

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